Chapter 3
Diagonal Design, Miter Gates

3-1. Diagonal Design

The following information is applicable to open frame gates and is essentially the same as that presented in "Torsional Deflection of Miter-Type Lock Gates and Design of the Diagonals" (USAED, Chicago, 1960) with only minor modifications.

3-2. Definitions of Terms and Symbols

Deviations from these symbols are noted at the places of exception.

Δ - Total torsional deflection of the leaf measured, at the miter end, by the movement of the top girder relative to the bottom girder. (See Figure 3-1.) The deflection is positive if the top of the miter end is moved upstream relative to the bottom.

Positive diagonal: A diagonal which decreased in length with a positive deflection of the leaf. (See Figure 3-4.)

a - The cross-sectional area of that part of a horizontal girder which lies outside the midpoint between the skin and the flange. (See Figure 3-6.)

A - Cross-sectional area of diagonal.

A'- Stiffness of the leaf in deforming the diagonal. Until more test data are available, it is suggested that A′ be taken as the sum of the average cross-sectional areas of the two vertical and two horizontal girders which bound a panel times:

1/8 for welded horizontally framed leaves with skin of flat plates,

1/20 for riveted vertically framed leaves with skin of buckle plate. (See paragraph 3-4*i*(1).)

b - Distance from the center line of the skin plate to the flange of a horizontal girder. (See Figure 3-6.)

c - The smaller dimension of a rectangular cross section.

d - Pitch diameter of the threaded portion of the diagonals.

D - Prestress deflection for a diagonal. D is the deflection of the leaf required to reduce the stress in a diagonal to zero. D is always positive for positive diagonals and negative for negative diagonals.

E - Bending modulus of elasticity.

E_s- Shearing modulus of elasticity.

h - Height of panel enclosing diagonal.

H - Vertical height over which H is measured, usually distance between top and bottom girders.

I - Moment of inertia about the vertical axis of any horizontal girder.

I_x- Moment of inertia, about the horizontal centroidal axis, of a vertical section through a leaf. (See Figure 3-5.)

J - Modified polar moment of inertia of the horizontal and vertical members of the leaf.

K - A constant, taken equal to 4. (See paragraph 3-4*i*(2).)

l - The larger dimension of a rectangular cross section.

L - Length of a diagonal, center to center of pins.

M - Torque required to turn the sleeve nut to prestress diagonal. (Refer to Equation 3-28.)

n - Number of threads per inch in sleeve nut of diagonal.

N - Number of turns of nut to prestress diagonal. (Refer to Equation 3-27.)

Q_o- Elasticity constant of a leaf without diagonals. (See paragraph 3-4*i*(2).)

Q - Elasticity constant of diagonal defined by Equation 3-18.

R_o - Ratio of change in length of diagonal to deflection of leaf when diagonal offers no resistance. (Refer to Equation 3-11.) R_o is positive for positive diagonals and negative for negative diagonals.

R - Ratio of actual change in length of diagonal to deflection of leaf. (Refer to Equation 3-13.) R is positive for positive diagonals and negative for negative diagonals.

s - Unit stress in diagonal.

S - Total force in diagonal.

t - Distance from center line of skin plate to center line of diagonal. (For curved skin plate, see paragraph 3-4*h*.)

T_z - Torque area. Product of the torque T of an applied load and the distance z to the load from the pintle. z is measured horizontally along the leaf. T_z is positive if the load produces a positive deflection.

v - Distance from center line of pintle to extreme miter end of leaf.

w - Width of panel. (Refer to Figure 3-1.)

X - Distance from center line of skin plate to vertical shear center axis of leaf. (Refer to Equation 3-30.)

y - Distance to any horizontal girder from the horizontal centroidal axis of a vertical section through a leaf.

y_n- Distance to any horizontal girder from the horizontal shear center axis of a vertical section through a leaf.

Y - Distance to horizontal shear center axis from the horizontal centroidal axis of a vertical section through a leaf. (Refer to Equation 3-29.)

3-3. Introduction

A lock-gate leaf is a very deep cantilever girder with a relatively short span. The skin plate is the web of this girder. If the ordinary equations for the deflection of a cantilever under shearing and bending stresses are applied, the vertical deflection of the average leaf will be found to be only a few hundredths of an inch. Because the skin plate imparts such a great vertical stiffness to the leaf, the stresses in the diagonals are a function of only the torsional (twisting) forces acting upon the leaf. These forces produce a considerable torsional deflection when the gate is being opened or closed. It is this torsional deflection and the accompanying stresses in the diagonals with which this chapter is concerned.

a. The shape of the twisted leaf is determined geometrically. Then the work done by the loads is equated to the internal work of the structure. From this, the resistance which each diagonal offers to twisting of the leaf is computed as a function of the torsional deflection of the leaf and the dimensions of the structure. Equations for torsional deflection of the leaf and stresses in the diagonals are derived.

b. Experiments were made on a model of the proposed gates for the MacArthur Lock at Sault Ste. Marie. Tests were also conducted in the field on the lower gates of the auxiliary lock at Louisville, KY. Both experiments indicate that the behavior of a gate leaf is accurately described by the torsional deflection theory.

c. Examples of the application of the theory are presented together with alternate methods for prestressing the diagonals of a leaf.

3-4. Geometry

In order to make a torsional analysis of a lock gate, the geometry of the deflected structure must be known. The change in length of the diagonal members will be determined as a function of the torsional deflection of the leaf. For the present, the restraint offered by the diagonals will not be considered.

a. Diagonal deformation. In Figures 3-2 and 3-3, the panel ak of Figure 3-1 is considered separately. As the leaf twists the panel ak twists as indicated by the dotted lines. In Figure 3-3, movements of all points are computed relative to the three reference axes gf, gb, and gk shown in Figure 3-2. The girders and skin plate are free to twist, but they remain rectangles, except for second-order displacements. Therefore, the three reference axes are always mutually perpendicular. Let δ_o equal the change in length of either diagonal of Figure 3-3.

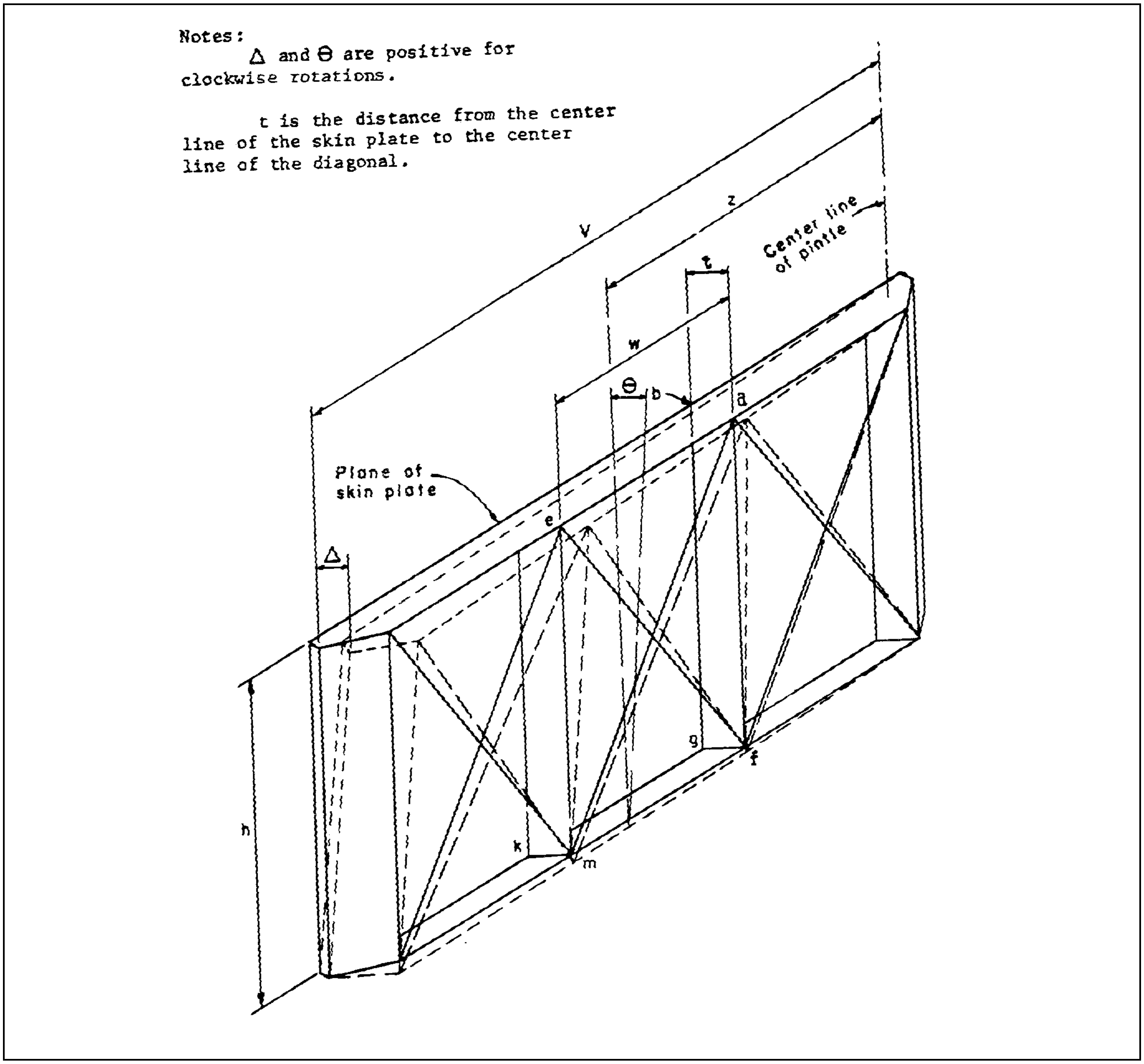


Figure 3-1. Schematic drawing of a typical miter-type lock-gate leaf

$$\delta_o = \frac{d}{w}\, t \cos\alpha + \left(\frac{d}{h}\, t \sin\alpha\right)$$
$$= \frac{dt}{w}\,\frac{w}{(w^2 + h^2)^{1/2}} + \frac{dt}{h}\,\frac{h}{(w^2 + h^2)^{1/2}} \qquad (3\text{-}1)$$
$$= \frac{2dt}{(w^2 + h^2)^{1/2}}$$

b. Sign convention. For the necessary sign convention, let the deflection *d* be positive when the top of the leaf moves upstream in relation to the bottom. With a positive deflection, those diagonals that decrease in length are considered positive diagonals. With negative deflection, where the top of the gate moves downstream in relation to the bottom, those diagonals that decrease in length are considered negative diagonals.

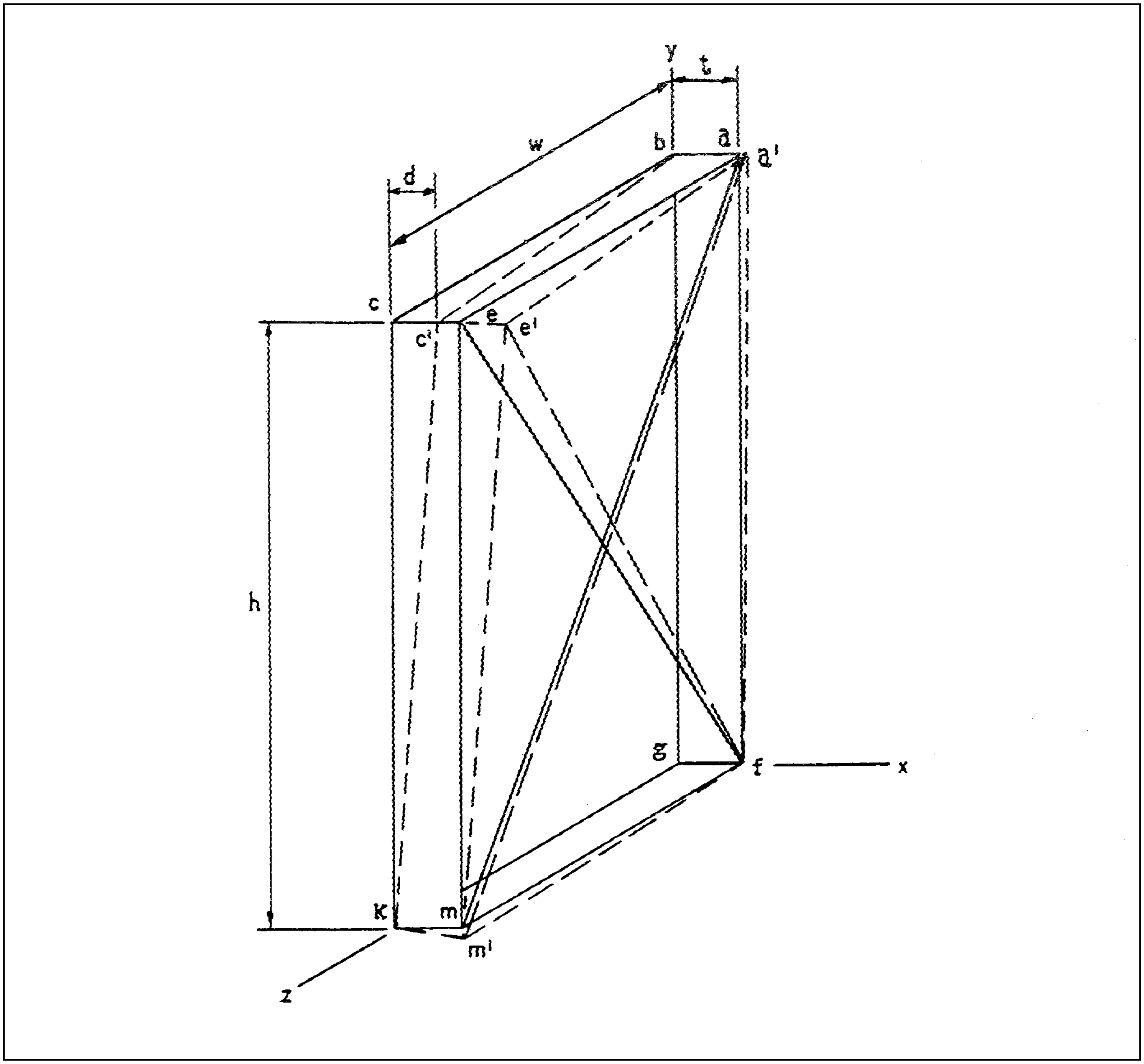


Figure 3-2. Schematic drawing of panel ak

c. Ratio of diagonal deformation to panel deflection. In the following information a decrease in any diagonal length, either positive or negative diagonal, is designated as a positive change in length. Let r_o be defined as follows:

$$r_o = \frac{\delta}{d}o \qquad (3\text{-}2)$$

which from Equation 3-1 becomes

$$r_o = \pm \frac{2t}{(w^2 + h^2)^{1/2}} \qquad (3\text{-}3)$$

r_o is positive for positive diagonals and negative for negative diagonals. Figure 3-4 illustrates the positive and negative diagonals of a typical leaf.

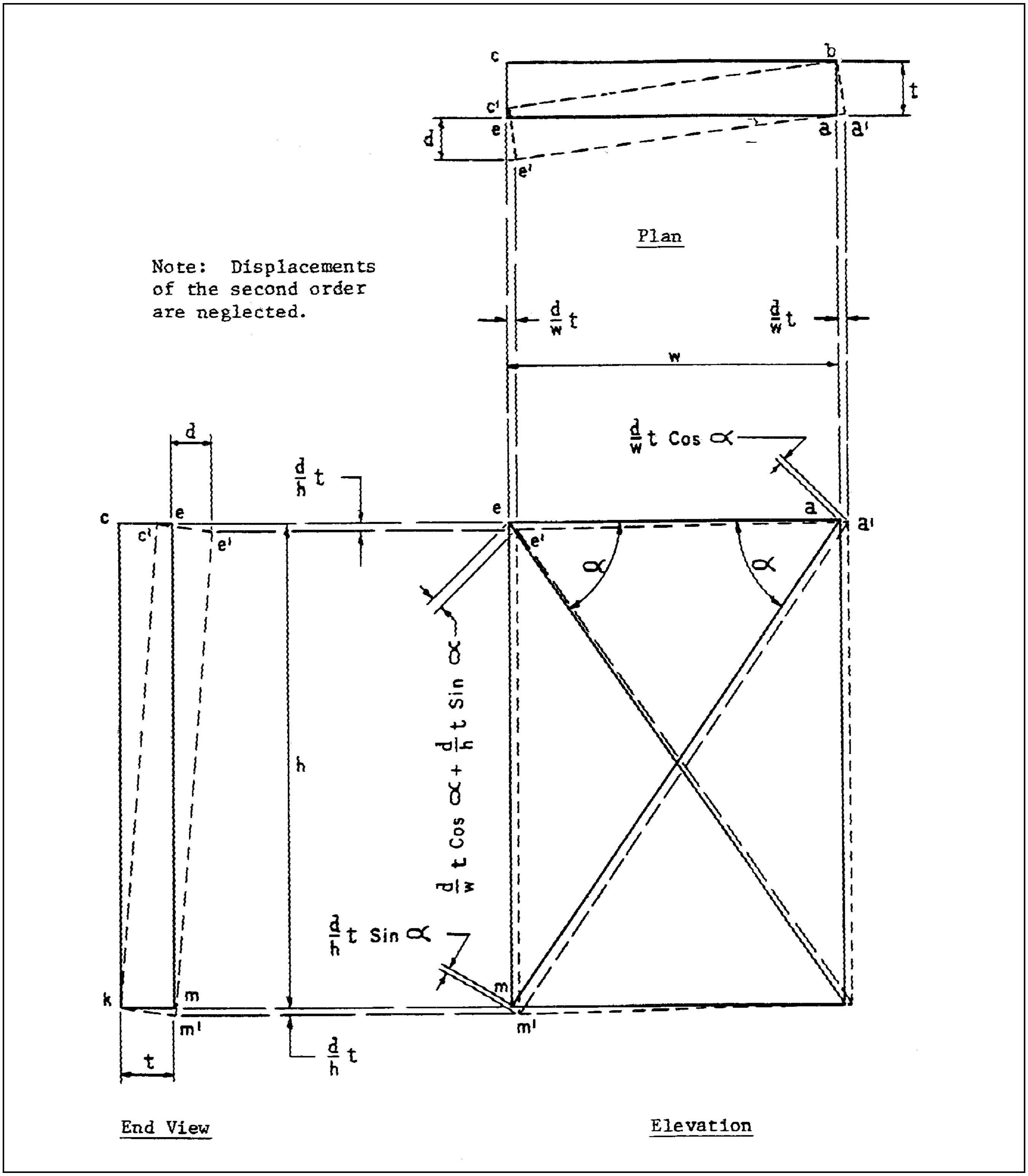


Figure 3-3. Displacements of points of panel ak

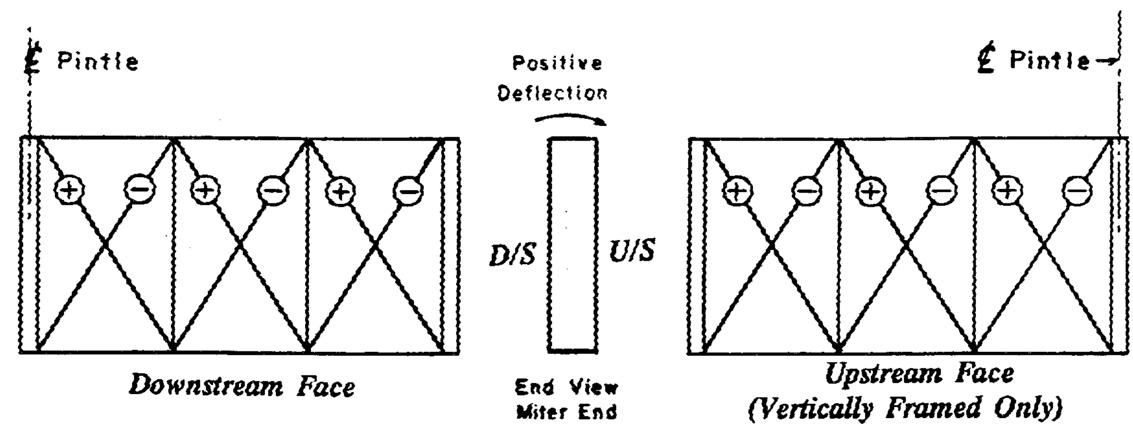


Figure 3-4. Positive and negative diagonals of a typical leaf

d. Diagonal restraint. Up to this point, the restraint offered by the diagonal members has not been considered. Equation 3-1 gives the change in length of a diagonal if the diagonal offers no resistance. However, unless a diagonal is slack, it does offer resistance to change in length. Therefore, when a deflection d is imposed upon the panel, the length of the diagonal does not change an amount δ_o. The actual deformation is δ which is less than δ_o by some amount δ′.

$$\delta = \delta_o - \delta' \qquad (3\text{-}4)$$

(1) It is evident that δ is inversely proportional to the resistance of the diagonal and that δ′ is inversely proportional to the ability of the panel to elongate the diagonal. Let the resistance of the diagonal be measured by its cross-sectional area *A*. Then

$$\frac{\delta}{\delta_1} = \frac{A'}{A} \qquad (3\text{-}5)$$

in which *A*′ is a measure of the stiffness of the panel in deforming the diagonal. The significance of *A*′ and the method of determining its magnitude will be discussed later. Let it be assumed for the present, however, that *A*′ is known.

(2) Solving Equation 3-4 for δ′ and substituting its value in Equation 3-5,

$$\frac{\delta}{\delta_o - \delta} = \frac{A'}{A} \qquad (3\text{-}6)$$

(3) Let *r* be defined as the ratio of the actual deformation of the diagonal to the deflection of the panel.

$$r = \frac{\delta}{d} \qquad (3\text{-}7)$$

(4) Using Equations 3-2 and 3-7, Equation 3-6 can be written

$$\frac{rd}{r_o d - rd} = \frac{A'}{A}$$

and solving for *r*

$$r = \frac{A'}{A + A'} r_o \qquad (3\text{-}8)$$

It will be noted that when the diagonal offers no restraint (that is to say that $A = o$), $r = r_o$.

(5) Let Δ be defined as the torsional deflection of the whole leaf; see Figure 3-1. It is evident that the relative deflection d from one end of a panel to the other is proportional to the width of the panel

$$d = \frac{w\ \Delta}{v} \tag{3-9}$$

(6) Let R_o be defined as follows:

$$R_o = \frac{\delta_o}{\Delta} \tag{3-10}$$

Substituting the values of δ_o and Δ from Equations 3-2 and 3-9, respectively

$$R_o = \frac{r_o d}{(v/w)d} = \frac{w r_o}{v}$$

which, from Equation 3-3, becomes

$$R_o = \pm \left(\frac{2wt}{v(w^2 + h^2)^{1/2}} \right) \tag{3-11}$$

Let R be defined by

$$R = \frac{\delta}{\Delta} \tag{3-12}$$

Substituting in Equation 3-12 the values of δ and Δ obtained from Equations 3-7 and 3-9, respectively

$$R = \frac{rd}{(v/w)d} = \frac{w}{v}\ r$$

which, from Equation 3-8 becomes

$$R = \frac{w}{v}\ r_o \frac{A'}{A + A'} = R_o \frac{A'}{A + A'} \tag{3-13}$$

e. Deflection of leaf and stresses in diagonals. In general, the diagonals of any lock-gate leaf will have, as a result of adjustments, an initial tension which is here called a prestress. The prestress in all diagonals is not the same. However, for any diagonal the leaf can be deflected by some amount Δ, such that the stress in that diagonal is reduced to zero. The magnitude of this deflection is a measure of the initial tension in the diagonal and will be called the prestress deflection D for that diagonal. By selecting the value of D, the designer can establish a definite prestress in any diagonal (see examples 1 and 2 in this chapter). It can be seen from the definition of a positive diagonal that D is positive for positive diagonals and negative for negative diagonals.

(1) Referring to Equation 3-12, it is seen that the prestress in any diagonal results from a change in length equal to R (-D). If an additional deflection Δ is imposed upon the leaf, the total change in length will be

$$\delta = R\ (-D) + R\ (\Delta) = R\ (\Delta - D) \tag{3-14}$$

and similarly

$$\delta_o = R_o(\Delta - D) \tag{3-14a}$$

Since a positive value of δ represents a decrease in length, the elongation of a diagonal is (-δ) and the total force is

$$S = \frac{(-\delta)\ EA}{L}$$

which from Equation 3-14 becomes

$$S = \frac{-REA}{L}\ (\Delta - D) \tag{3-15}$$

(2) If the diagonal offered no resistance to change in length, its deformation would be, from Equation 3-4, δ_o

$= \delta + \delta'$. The force in the diagonal, therefore, not only elongates the diagonal an amount δ'. The total work done by the force S in the diagonal is, therefore

$$W_D = \frac{1}{2}(\delta + \delta') = \frac{1}{2} S\delta_o$$

which, by adapting Equation 3-14a, becomes

$$W_D = \frac{1}{2} SR_o (\Delta - D) \qquad (3\text{-}15a)$$

Substituting the value of S from Equation 3-15

$$W_D = \frac{-RR_oEA}{2L} (\Delta - D)^2 \qquad (3\text{-}16)$$

(3) The force S in the diagonal is produced by some external torque T. The work done is

$$W_T = \frac{1}{2} T\theta$$

It is evident from Figure 3-1 that the angle of rotation θ of any section of the leaf is proportional to the distance z from the pintle. If the leaf is twisted an amount (Δ-D), the angle of rotation at the end is (Δ-D)/h. Therefore, at any section

$$\theta = \frac{(\Delta - D)}{h} \frac{z}{v}$$

Making this substitution for 0 in the equation for W_T

$$W_T = \frac{(\Delta - D)}{2hv} T_z \qquad (3\text{-}17)$$

The term T_z is the area of the torque diagram for the torque T. T_z will hereinafter be called "torque-area." (See definitions.)

(4) Equating the sum of W_D and W_T as given by Equations 3-16 and 3-17, respectively, to zero and simplifying

$$T_z - \frac{RR_oEAhv}{L} (\Delta - D) = 0$$

Let

$$Q = \frac{RR_oEAhv}{L} \qquad (3\text{-}18)$$

Then

$$T_z + Q (D - \Delta) = 0 \qquad (3\text{-}19)$$

Since T_z is the torque-area of the external load, the quantity $Q(D$-$\Delta)$ may be called the resisting torque-area of the diagonal. All factors of Q are constant for any diagonal. Q, therefore, is an elasticity constant of the diagonal. Even if there were no diagonals on a leaf, the structure would have some resistance to twisting. Let the resisting torque-area of the leaf without diagonals be defined as $Q_o(\Delta)$. A prestress deflection D is not included in this definition since the leaf does not exert any torsional resistance when it is plumb. In other words, D for the leaf is zero. Q_o will be evaluated later. For the present, let it be assumed that Q_o is known.

(5) The total torque-area of all external loads plus the torque-area of all resisting members must equal zero. Therefore, Equation 3-19 may be written as follows:

$$\Sigma (T_z) - Q_o\Delta + \Sigma [Q (D - \Delta)] = 0 \qquad (3\text{-}20)$$

in which $\Sigma[Q(D$-$\Delta)]$ includes all diagonals of the leaf.

(6) Since Δ is a constant for any condition of loading, Equation 3-20 may be solved for Δ.

$$\Delta = \frac{\Sigma (T_z) + \Sigma (QD)}{Q_0 + \Sigma Q} \qquad (3\text{-}21)$$

which is the fundamental equation for deflection.

(7) If the leaf is to hang plumb ($\Delta = 0$) under dead load, the numerator of the right-hand member of Equation 3-21 must equal zero.

$$\Sigma(T_z)_{D.L.} + \Sigma(QD) = 0 \tag{3-22}$$

Equation 3-22 represents the necessary and sufficient condition that a leaf hang plumb under dead load.

(8) If the live-load and dead-load torque-areas are separated, Equation 3-21 may be written

$$\Delta = \frac{\Sigma\,(T_z)_{L.L.} + \Sigma\,(T_z)_{D.L.} + \Sigma\,(QD)}{Q_o + \Sigma Q}$$

But if Equation 3-22 is satisfied, $\sum(T_z)_{D.L.} + \sum(QD) = 0$

Therefore

$$\Delta = \frac{\Sigma\,(T_z)_{L.L.}}{Q_o + \Sigma Q} \tag{3-23}$$

which is the fundamental equation for deflection of a leaf with all diagonals prestressed. Equation 3-23 shows that the live load deflection of a leaf is independent of the prestress deflection D for any diagonal.

(9) The unit stress in a diagonal is obtained by dividing Equation 3-15 by A,

$$s = \frac{RE}{L}\,(D - \Delta) \tag{3-24}$$

which is the fundamental equation for unit stress in a diagonal.

(10) If the maximum allowable unit stress is substituted for s in Equation 3-24, the maximum allowable numerical value of (D-Δ) will be obtained. Since the maximum values of Δ are known from Equation 3-23, the maximum numerical value of D for any diagonal can be determined.

(11) The diagonals of a gate leaf should be prestressed so that all of them are always in tension (see paragraph 3-4*j*). If this is to be so, the quantity (D-Δ) must always represent an elongation of the diagonal. Therefore, for positive diagonals, D must be positive and greater than the maximum positive value of Δ. For negative diagonals, D must be negative and numerically greater than the maximum negative deflection. These then are the minimum numerical values of D.

(12) Values of D shall be selected such that they satisfy Equation 3-22 and lie within the limits specified above. If this is done, the leaf will hang plumb under dead load, and none of the diagonals will ever become overstressed or slack. In addition, the deflection of the leaf will be held to a minimum since a prestressed tension diagonal is in effect a compression diagonal as well.

f. Preliminary area of diagonals. In the design of diagonals, it is desirable to have a direct means of determining their approximate required areas. With these areas, the deflection and stresses can then be found and, if considered unacceptable, the areas could be revised and the process repeated. A close approximation to the required area can be found by equating Equations 3-15a and 3-17.

$$\frac{1}{2}\,SR_o\,(\Delta - D) = -\frac{(\Delta - D)}{2hv}\,T_z$$

Treating R_o as equal for all diagonals, substituting sA for S, and taking $\sum$ for all diagonals in a set,

$$A = -\frac{\Sigma\,T_z}{R_o hv} \tag{3-25}$$

With the above, the maximum positive $\sum T_z$ will give the total area required in the set of negative diagonals and the maximum negative $\sum T_z$, the area for the positive diagonals.

g. Vertical paneling of leaf. By differentiating Q with respect to h, it has been found that the most effective slope for a diagonal exists with $h = w(2)^{1/2}$. If h approaches 2.5 w, it will be desirable to subdivide the panel vertically to reduce the area of the diagonals or, possibly, to reduce their total cost. The example in paragraph 3-6*i* shows the slight modification necessary to apply this method of design to panels subdivided vertically. In general, diagonals are most effective in panels having the ratio of

$$\frac{\text{Greater dimension}}{\text{Lesser dimension}} \approx (2)^{1/2}$$

h. Curved skin plate. The geometric relationships derived herein apply equally well to a leaf with curved or stepped skin plating and the more general value of t is the plan view divided by the width. The plan-view area is the area bounded by the skin plate, the center line of the diagonals, and the side boundaries of the panel.

i. Discussion.

(1) The constant A': Except for the constants A' and $Q_{o'}$ all properties of the gate leaf are known, and the deflection of the leaf and the stresses in the diagonals can be determined. A' appears in the equations for both R and Q as follows:

$$R = \frac{A'}{A + A'} R_o \tag{3-13}$$

$$Q = \frac{RR_o EAhv}{L} + \frac{R_o 2EAhv}{L} \times \frac{A'}{A + A'} \tag{3-18}$$

(a) Measurements were made on the 1/32-size celluloid model of the gates for the MacArthur Lock at Sault Ste. Marie (Soo). Field measurements were also made on the lower gate at Louisville, KY, and 29 gate leaves in the Rock Island District on the Mississippi River. The Soo and Louisville gates are horizontally framed and have flat skin plates and the Mississippi gates are vertically framed and have buckle skin plates. In all cases, δ was determined from strain gage readings on the diagonal and Δ was measured directly as the leaf was twisted. Equation 3-12 gave the value of R. A' was then calculated from Equation 3-12 in which the theoretical value of R_o, obtained from Equation 3-11 was substituted.[1] Values of A' obtained are:

Sault Ste.
Marie A' = 0.025 in.^{2} (model)
= 0.025 x (32)^2 = 26 in.^{2} (prototype)

Louisville = 13 in.^{2}

Mississippi
River Gates = 10 in.^{2}

(b) It seems reasonable to suppose that the size of the horizontal and vertical girders to which the diagonal is attached can be used as a measure of A'. At Sault Ste. Marie, A' is 0.14 of the sum of the cross-sectional areas of the girders which bound the diagonal. At Louisville the factor is 0.07 and for the Mississippi River gates, 0.045. Additional experiments are desirable. However, until more data are obtained, it is believed that a conservative value of A' for the average diagonal is the sum of the average cross-sectional areas of the girders which bound the diagonals times 1/8 for the heavier, welded, horizontally framed leaves with flat skin plate and 1/20 for the lighter, riveted, vertically framed leaves with buckle plates.

(c) It is believed that for any gate leaf diagonal, A' will usually be as large or larger than A. Therefore, a large error in A' will result in a much smaller error in the fraction $A'/(A + A')$. Hence, it is necessary to know the approximate value of A' in order to apply the foregoing theory. This is especially true of the diagonal stress, as can be seen from Equation 3-24 where an error in A' produces an error R which is opposite to that produced in $(D - \Delta)$. Thus, stress is nearly independent of A'.

(2) The constant Q_o: Q_o is an elasticity constant which is a measure of the torsional stiffness of a leaf without diagonals. Q_o is a function of many properties of the leaf. However, it seems reasonable that the torsional work done upon the typical main members of the leaf, as the leaf twists, might be used as a measure of Q_o.

(a) When a leaf twists, the horizontal and vertical members rotate through angles of Δ/h and Δ/v, respectively. The work done in any member is

$$W = \frac{1}{2} \frac{E_s J}{v} \frac{(\Delta)^2}{h^2} \text{, for horizontal members}$$

$$W = \frac{1}{2} \frac{E_s J}{h} \frac{(\Delta)^2}{v^2} \text{, for vertical members}$$

E_s = shearing modulus of elasticity

J = modified polar moment of inertia

The work done by an external torque is, from Equation 3-17

$$W_T = \frac{\Delta}{2hv} T_z$$

[1] In the model test, the experimental value of R_o was also determined and was found to agree with the theoretical value within 1 percent.

In this case the value of D in Equation 3-17 is zero since the members are not supplying a resisting torque when the deflection is zero. Equating W_T to W and solving T_z,

$$T_z = \frac{E_s J}{h} \Delta \text{ , for horizontal members}$$

$$T_z = \frac{E_s J}{v} \Delta \text{ , for vertical members}$$

The quantities $E_s J/h$ and $E_s J/v$ might be called the values of Q_o for

horizontal and vertical members, respectively, hence,

$$Q_o = K\ E_s\ \Sigma\ (J/h\ +\ J/V) \tag{3-26}$$

where the value of K as determined experimentally for the Sault Ste. Marie model and the Louisville prototype is approximately 4. Until additional measurements can be made, this value should be used.

(b) Nearly all members of a leaf subject to torsion are made up of narrow rectangles. For these, the value of J is

$$\frac{\Sigma\ l\ (3)^3}{3}$$

Where plates are riveted or welded together, with their surfaces in contact, they are considered to act as a unit with c equal to their combined thickness.

(c) Using Equation 3-26, Q_o can be evaluated very easily, as will be demonstrated in the examples. However, in many cases Q_o can be neglected entirely without being overly conservative. In neglecting Q_o, the stiffness of the leaf itself, without diagonals, is neglected. An experiment has shown this stiffness to be small. Furthermore, anyone who has seen structural steel shapes handled knows how easily they twist. Unless closed sections are formed, the total stiffness of a leaf is just the arithmetic sum of the stiffness of all members taken individually and this sum can be shown to be small. The lack of torsional stiffness is also illustrated by a known case in which a leaf erected without diagonals twisted several feet out of plumb under its own dead weight. Q_o is included in examples 1 and 2 but its values are only 5 percent and 3 percent, respectively, of the total stiffnesses, Q, contributed by the diagonals.

(3) Load torque-areas. By definition, a load applied through the shear center of a section will cause no twisting of the section. In computing dead load torque-area the moment arm of the dead load is, therefore, the distance from the vertical plane through the shear center to the center of gravity of the leaf. The method of locating the shear center of a lock-gate leaf is given in paragraph 3-4*k*. The water offers resistance against the submerged portion of the leaf as it is swung. There is also an inertial resistance to stopping and starting. Since the resultant of these resistances is located near or below the center height of leaf and the operating force is near the top of the leaf, a live load torsion results. From tests performed to determine operating machinery design loads, the maximum value of the above-mentioned resistances was found to be equivalent to a resistance of 30 psf on the submerged portion of the leaf. Until additional data become available, it is recommended that this value be generally used in computing the live load torque-area. However, in the case of locks accommodating deep-draft vessels, water surges are created during lockages that appear to exceed the above-mentioned equivalent load. Until more data are obtained, it is recommended that for these cases, 45 psf or higher be used.[2] The diagonals will also be checked for obstruction loads and temporal hydraulic loads and the governing loading condition will be used for diagonal design. For definition of obstruction and temporal hydraulic loads, refer to paragraphs 2-1*b* and 3-8, respectively.

(4) Skin plate consisting of buckle plates. The theory is based upon the assumption that the skin plate remains rectangular at all times. If the skin consists entirely of buckle plates and if the shear in the skin is large, this assumption may be in error. However, if the diagonals extending downward toward the miter end are made larger or prestressed higher than the others, the prestress in them can be made to carry a large part, if not all, of the dead load shear. Although the action of buckle plates in shear is not understood, it is recommended that they be treated as flat plates. As a precaution, however, the diagonals should be prestressed to carry as much of the dead load as possible within the restrictions imposed upon D (see paragraph 3-4*e*). The reader is referred to example 2, paragraph 3-6.

j. *Methods for prestressing diagonals*. It is essential that all diagonals be prestressed. With all diagonals

[2] The operating strut mechanism should also then be designed for these larger forces.

prestressed, none will ever alternately bow out and then snap back into position during operation of the leaf. It is certain that this buckling was responsible for some of the failures of diagonals which occurred in the past. Prestressing also reduces the torsional deflection of the leaf to a minimum, since all diagonals are always acting. There are two general methods of prestressing diagonals. In one method, the leaf is twisted a precomputed amount and the slack in the diagonals is removed. In the other, the sleeve nut on the diagonal is turned a precomputed amount. Caution should be taken when using the twist of the leaf method where the leaf has top and bottom torque tubes. Due to the increased leaf stiffness, there is the need for a higher jack capacity (150+ tons), and a possibility that damage could be caused to the leaf or other gate components. The high jacking loads could cause damage such as localized buckling of plates, excessive deflection in the quoin post, damage to the grease seals, pintle, and pintle socket, etc. These two methods are discussed below:

(1) Twist-of-the-leaf-method. The quoin end of the leaf is made plumb and the miter end is anchored to prevent horizontal movement in either direction. This is done by either tying the miter end to the sill or tying the top miter end to the lock wall and using a hydraulic jack at the bottom. Then with a power-operated cable attached to the top of the miter end, the leaf is twisted the computed D for one set of diagonals and the slack is removed from this set. During this operation, the other set of diagonals must be maintained slack. The leaf is then twisted in the opposite direction the computed D for the other set of diagonals, and the slack is removed from them. (See example 2, paragraph 3-6.) It is important that all the slack be removed without introducing any significant tension in the diagonal. This can best be accomplished by lubricating the nut and manually turning it with a short wrench. Since the turning resistance increases abruptly with the removal of the slack, the point of removal can be felt. As a further precaution, a strain gage is recommended on the diagonal being tightened. The maintained deflection of the leaf should also be watched, since more than a slight tension in the diagonal will cause a change in deflection of the leaf. On existing gates in which the diagonals were not designed by this method, it may be necessary to overstress some diagonals during the prestress operation. A stress of $0.67F_y$ for this one-time load is considered permissible where F_y is the yield strength of the diagonal material. The prestressing force required (normal to the leaf, at the upper miter corner) is obtained from Equation 3-21 as

$$p = \frac{\Delta\ (Q_o = \Sigma Q) - \Sigma Q - (\Sigma T_z)\ D.L.}{hv}$$

where Q includes only the active diagonals. (See the example, paragraph 3-6*i*.)

(2) Turn-of-the-nut-method. In this method, it is essential that the nut be very well lubricated with a heavy lubricant. Initially, all diagonals must be slack and, during the prestressing operation, each diagonal must be maintained slack until it is reached in the prestressing sequence. Then the slack is removed from the first diagonal to be prestressed and the diagonal is clamped to the leaf, as close to both ends of the nut as possible, to prevent twisting of the diagonal during the nut-turning operation. The clamping should restrain twisting of the diagonal without preventing elongation of the full length. In removing the slack, the same precautions should be observed as in the previous method. The nut is then turned the precomputed N for the diagonal. This procedure is repeated for each succeeding diagonal. (See example 1, paragraph 3-5.) The large torque required to fully tighten the nut can be provided by a mechanically supplied force at the end of a long wrench. The nut must be turned to shorten the diagonal an amount $\delta_o = R_o\ (D\text{-}\Delta)$. Therefore, if n is the number of threads per inch, the number of turns required is

$$N = \frac{nR_o(D-\Delta)}{2} \qquad (3\text{-}27)$$

in which Δ is the initial deflection measured in the field. From textbooks on machine design, the torque M required to turn the nut to obtain the desired prestress, sA, is

$$M = sA\ \tan\ (\theta + \alpha) d$$

where d is the pitch diameter of the threads, θ is the friction angle which from tests may be taken equal to $\tan^{-1}(0.15) = 8^o30'$, and α is the helix angle which, within the size range that would be used on diagonals, may be taken as a constant angle of $1^o30'$. Further the maximum unit stress s is given by Equation 3-24.

Therefore

$$M = 0.18\ sAd = \frac{0.18\ REAd(D-\Delta)}{L} \qquad (3\text{-}28)$$

in which Δ is determined from Equation (3-21), with only the active diagonals included.

(3) Comparison of methods. The twist-of-the-leaf method has been used, with excellent results, considerably more than the turn-of-the-nut method. While the turn-of-the-nut method appears to have some merit, such as reduction in setup time, the elimination of overstressing any diagonal during prestressing, and the elimination of strain gages, this method is not recommended due to the difficulties encountered during prestressing. The diagonal bar tends to twist and it is extremely difficult to provide sufficient torque to the sleeve nut or turnbuckle without first deflecting the leaf. The turn-of-the-nut method is included for information but for normal installations the twist-of-the-leaf method should be used.

k. General method for locating shear center of a lock gate leaf. The shear center of a gate leaf is the point through which loads must be applied if the leaf is not to twist.

(1) Horizontal shear center axis. Consider the leaf restrained against rotation about the hinge. To prevent twisting of the leaf due to horizontal forces, the resultant of these forces must be located so that the load to each horizontal girder is proportional to their relative stiffnesses. This is equivalent to saying that the resultant must be located along the horizontal gravity axis of the girder stiffnesses. This gravity axis is then the horizontal shear center axis and is located a distance from the centroidal axis equal to

$$Y = \frac{\Sigma(I_n\ Y)}{\Sigma I_n} \tag{3-29}$$

in which I_n is the moment of inertia of any horizontal girder about its vertical centroidal axis.

(2) Vertical shear center axis. A lock-gate leaf is a cantilever beam supported by the pintle gudgeon. A vertical load on the leaf causes tension above and compression below the centroidal axis. Therefore, longitudinal shearing stresses exist in the structure and shearing stresses of equal magnitude and at right angles to the longitudinal shearing stresses exist in the plane of any vertical cross section.

(a) A shear diagram with arrows to indicate the direction of the shear is shown in Figure 3-5. Since the shears of the flanges of the top and bottom girders are small and since the shear on one side of a flange is usually equal and opposite to the shear on the other side of the same flange, these shears will be neglected. The horizontal shears in the webs of the top and bottom girders produce a torsional moment on the section which must be balanced by the torsional moment VX of the vertical forces if the leaf is not to twist.

(b) The shear diagram for the web of the right-hand part of the top girder is redrawn to a larger scale in Figure 3-6. The trapezoidal shape of this diagram is based upon the assumption that the thickness of the web is constant within the limits of the diagram. The ordinate of the diagram at any point is VQ/I. The area of the shear diagram is the total horizontal shear S on this part of the girder. This area is $(VQ/I)b$ in which VQ/I is the ordinate at the center of the diagram. Therefore, Q is the statical moment, about the centroidal axis of the whole section, of that part of the section lying within the circle of Figure 3-6. If a is the area of this part of the section, then $Q = ay$, and

$$S = \frac{Vay}{I}\ b$$

The torsional moment of all these horizontal shearing forces about the horizontal shear center axis is

$$T = \Sigma\ \frac{Vay}{I}\ by_n = \frac{V}{I}\ \Sigma(ayby_n)$$

If the leaf is not to twist, the sum of the moments of the vertical and horizontal forces must equal zero.

$$VX + \frac{V}{I}\ \Sigma(ayby_n) = 0$$

and solving

$$X = -\left[\frac{\Sigma(ayby_n)}{I}\right] \tag{3-30}$$

which is the horizontal distance from the center line of the skin to the shear center of the section. In this equation, a is always positive and b and X are positive when measured to the right of the skin and negative when measured to the left.

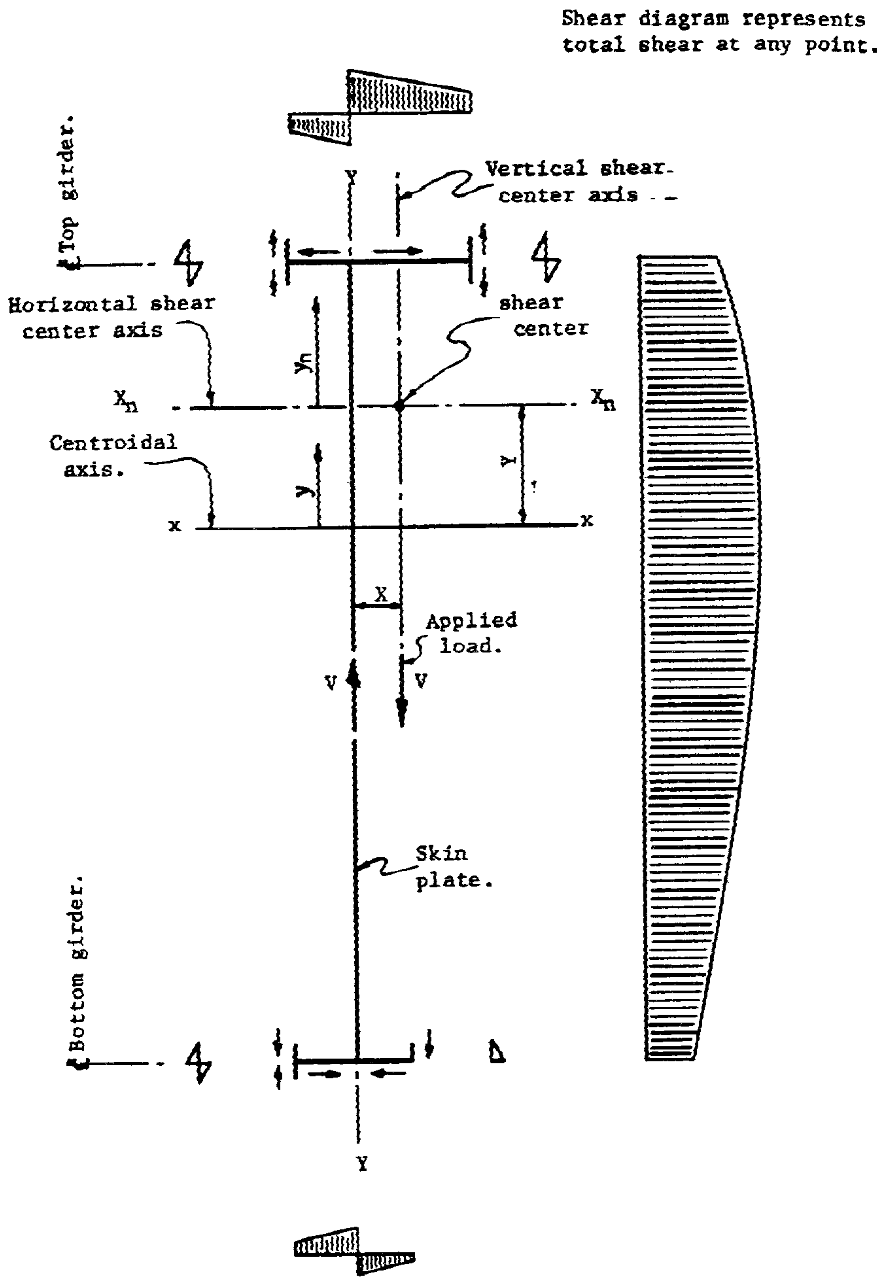


Figure 3-5. Shear diagram for typical vertically framed lock-gate leaf

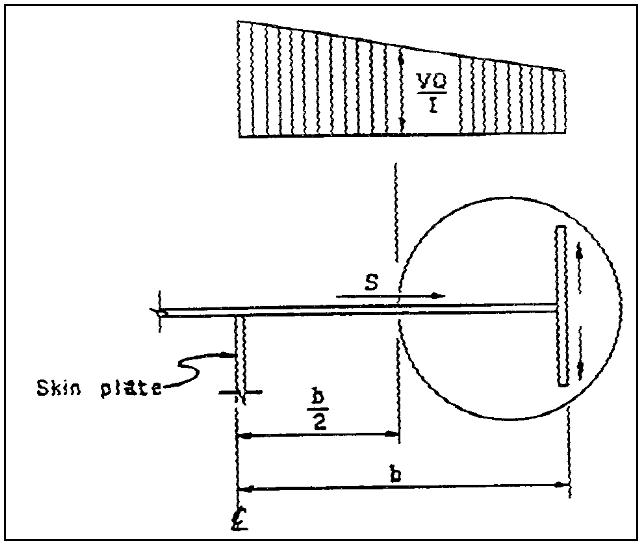


Figure 3-6. Shear diagram for web of the right-hand part of the top girder

c. Equations 3-29 and 3-30 are general expressions, independent of the number of horizontal girders, and as such apply equally well to horizontally framed gates.

3-5. Example 1, Horizontally Framed Gate

Lower operating gates, MacArthur Lock, Sault Ste. Marie (See Figure 3-7).

a. Evaluation of A′. The bottom and top girders and the vertical end girders are W36X150 with a cross-sectional area of 44.16 in^2. Therefore, A' is (see paragraph 3-4*i*(1))

$$A' = 1/8\ (4 \times 44.16) = 22\ \text{in.}^2$$

b. Evaluation of Q_o. (See paragraph 3-4*i*(2) and Table 3-1.)

$$Q_o = K\ E_s\ \Sigma(j/h + j/v)$$

$$Q_o = 4 \times 12 \times 10^6\ \frac{4320.0}{3 \times 684.0} + \frac{590}{3 \times 529} = 120.0 \times 10^6\ \text{in. lb.} \tag{3-26}$$

c. Location of shear center. (See Figure 3-5.) Computations for the centroidal axis and moment of inertia of the vertical section through the leaf (see Figure 3-7) are not given. Computations of distances *x* and *y* are given in Tables 3-2 and 3-3, respectively.

y = 310 in. I = 42.6 x 106 in.^{4}

Horizontal shear center axis:

$$Y = \frac{\Sigma(I_n \cdot y)}{\Sigma I_n} = \frac{-1.61\ x\ 10^6}{162{,}000} = -10.0\ \text{in.} \tag{3-29}$$

Vertical shear center axis:

The value of *b* for all girders is -36.1 in.

$$X = -\frac{b}{I}\Sigma(ayy_n) = -\left(\frac{-36.1}{42.6 \times 10^6}\right) x\ 13.54 \times 10^6 = 11.4\ \text{in.} \tag{3-30}$$

d. Load torque areas. (See paragraph 3-4*i*(3).) The forces which produce twisting of the leaf are shown in Figure 3-8. Computation of the torque area is given in Table 3-4. Computations for the location of the center of gravity and deadweight of the leaf are not given. Because this lock handles deep-draft vessels, a water resistance of 45 psf is used.

e. Evaluation of R_o, R, and Q.

$$R_o = \pm\ \frac{2wt}{v(w^2 + h^2)^{½}} = \pm\ \frac{2 \times 483 \times 37.8}{529\ (483^2 + 684^2)^{½}} = \pm 0.0822$$

Required size of diagonals:

For diagonal U_oL_1,

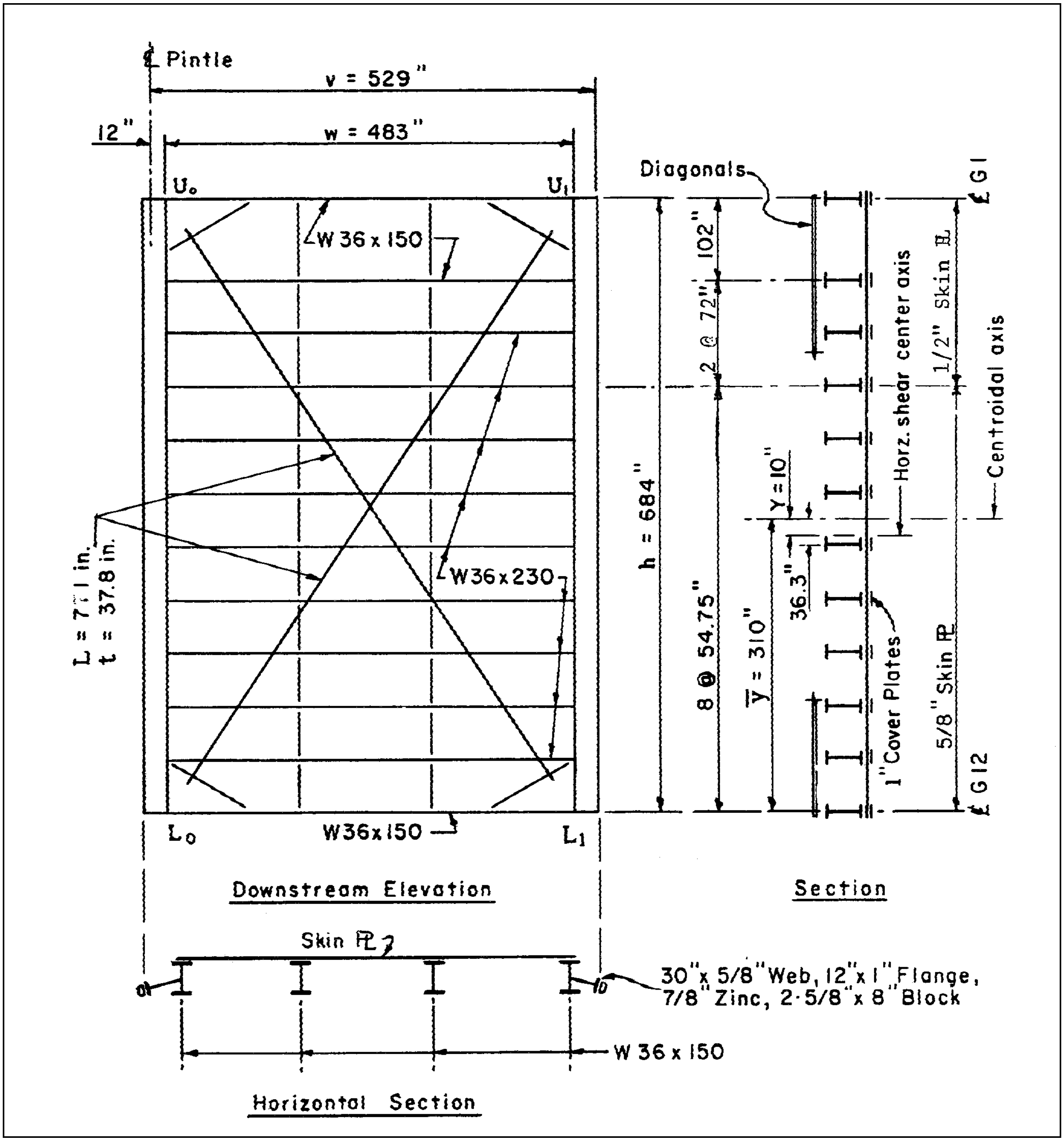


Figure 3-7. Lower gate leaf, MacArthur Lock, Sault Ste. Marie

Table 3-1
Computation of Modified Polar Moment of Inertia J

Elements	n (No. of Elements)	1 (in.)	c (in.)	nlc^3 Horizontal Members	Vertical Members
Horizontal Girders					
US flange,	3	12.0	2.44	520.0	-
Web,	3	34.0	0.63	30.0	-
DS flange, (G1, 2, and 12)	3	12.0	0.94	30.0	-
US flange,	9	16.5	2.78	3190.0	-
Web,	9	33.5	0.77	140.0	-
DS flange, (G3 through G11)	9	16.5	1.26	300.0	-
Skin (between flanges)					
1/2" plate	1	203.0	0.50	30.0	-
5/8" plate	1	308.0	0.63	80.0	-
Vertical Girders					
US flange	4	12.0	1.57	-	190.0
Web	4	34.0	0.62	-	30.0
DS flange	4	12.0	0.94	-	40.0
Quoin & Miter Posts					
Web	2	30.0	0.63	-	20.0
Flange	2	12.0	1.00	-	20.0
Block	2	8.0	2.63	-	290.0
		Total	=	4320.0	590.0

Table 3-2
Computation of Distance Y

Girder	I_n(in.^{4})	y (in.)	$I_{n.y}$(in.^{5} x 10^6)
G-1	9,000	+374.0	+3.37
G-2	9,000	+272.0	+2.44
G-3	15,000	+200.0	+3.00
G-4	15,000	+128.0	+1.92
G-5	15,000	+ 73.3	+1.10
G-6	15,000	+ 18.5	+0.28
G-7	15,000	+ 36.3	- 0.55
G-8	15,000	- 91.0	- 1.36
G-9	15,000	- 145.8	- 2.18
G-10	15,000	- 200.5	- 3.00
G-11	15,000	- 255.3	- 3.84
G-12	9,000	- 310.0	- 2.79
Σ	162,000		- 1.61

$$A = -\Sigma \frac{T_z}{sR_o hv}$$

$$= -\left(\frac{-11{,}570 \times 10^6}{18{,}000 \times 0.0822 \times 684 \times 529}\right) \qquad (3\text{-}25)$$

$$= 21.5 \text{ in.}^2$$

For diagonal L_oU_1,

$$A = -\left(\frac{9{,}200 \times 10^6}{18{,}000 \times 0.0822 \times 684 \times 529}\right)$$

$$= 17.1 \text{ in.}^2$$

Table 3-3
Computation of Distance X

Girder	a(in.^{2})	Y(in.)	Y_n(in.)	ayy_n(in.^{4} x 10^6)
G-1	22.1	+374.0	+384.0	3.17
G-2	22.1	+272.0	+282.0	1.69
G-3	33.9	+200.0	+210.0	1.42
G-4	33.9	+128.0	+138.0	0.60
G-5	33.9	+ 73.3	+ 83.3	0.21
G-6	33.9	+ 18.5	+ 28.5	0.02
G-7	33.9	- 36.3	- 26.3	0.03
G-8	33.9	- 91.0	- 81.0	0.25
G-9	33.9	- 145.8	- 135.8	0.67
G-10	33.9	- 200.5	- 190.5	1.29
G-11	33.9	- 255.3	- 245.3	2.13
G-12	22.1	- 310.0	- 300.0	2.06
			Σ	13.54

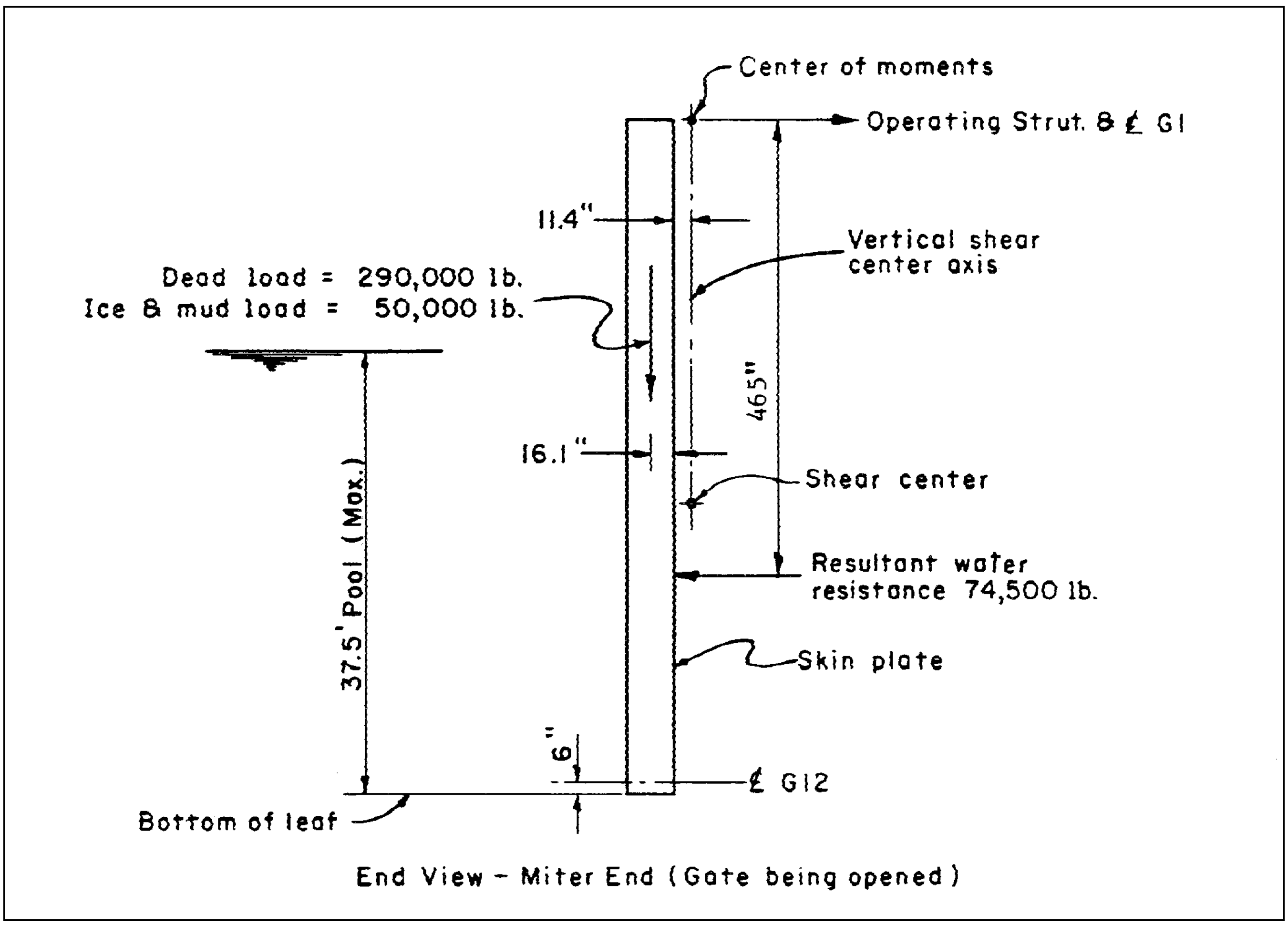


Figure 3-8. Forces acting on leaf being opened

Table 3-4
Computation of Torque Area

Load	Force (lb)	Moment arm (in.)	z (in.)	T_z(in.^{2}lb x 10^6)
Dead load	290,000	27.5[a]	253	- 2,020
Ice & mud	50,000	27.5	253	-350
Water	74,500	465.0	265	±9,200[b]

[a] From determinations of shear center and center of gravity for various horizontally framed gates, this arm is approximately 3/4t.
[b] Plus value for gate opening.

For diagonal L_oU_1, the dead load torque is not now included since diagonal U_oL_1 will be prestressed to support this load. The following diagonal sizes will be used throughout the remainder of the design and revised later, if necessary.

U_oL_1 - 24.0 in.^{2} (2 @ 12 in.^{2})

L_oU_1 - 18.0 in.^{2} (2 @ 9 in.^{2})

$$R = \frac{A'}{A + A'} R_o = \pm\frac{22}{A+22} \times 0.822) \tag{3-13}$$

$$Q = \frac{RR_oEAhv}{L}$$

$$= \frac{R \times 0.0822 \times 29 \times 10^6 \times A \times 684 \times 529}{771}$$

$$= 112 \times 10^7 \times RA$$

Computation of the constant Q is given in Table 3-5.

Table 3-5
Computation of Constant Q

Diagonal	A (in.^{2})	R	Q (in.-lb × 10^6)
U_oL_1	24.0	+0.0393	1,050.
L_oU_1	18.0	-0.0452	910.
			ΣQ = 1,960.

f. Deflection of leaf.

$$\text{Gate opening} \quad \Delta = \frac{\Sigma T_z}{Q_o + \Sigma Q}$$

$$= \frac{9,200 \times 10^6}{(120 + 1,960) \times 10^6} \tag{3-23}$$

$$= 4.4$$

$$\text{Gate closing} \quad \Delta = \frac{(-9,200 - 350) \times 10^6}{(120 + 1,960) \times 10^6}$$

$$= -4.6$$

g. Prestressed deflections and stresses in diagonals. Prestress deflections are determined in Table 3-6. The minimum numerical values of D (line 3) are the maximum deflections of the leaf. Maximum numerical values of (D - Δ) are found by solving Equation 3-24.

$$(D - \Delta) = \frac{sL}{RE} = \frac{18,000 \times 771}{R \times 29 \times 10^6} = \frac{0.478}{R}$$

Having the maximum numerical values of (D - Δ), the maximum values of D are determined and placed in line 5. Values of D (line 6) are then selected between the above limits such that Equation 3-22 is satisfied; that is, $\sum(QD)$ must equal +2,020 × 10^6in.^{2}lb. Further, to ensure that the diagonals will always be in tension, D should be such that the minimum stress is more than

Table 3-6
Stresses in Diagonals During Normal Operation

Line	Parameter	Positive Diagonal U_oL_1	Negative Diagonal L_oU_1
1	R	+0.0393	-0.0452
2	Q (in.-lb. $\times$ 10^6)	1,050	910
3	Minimum numerical value of D (in.)	+4.4	-4.6
4	Maximum numerical value of D-Δ) (in.)	+12.1	-10.6
5	Maxumum numerical value of D (in.)	+7.5	-6.2
6	D (selected value) (in.)	+6.7	-5.5
7	QD (in.^{2}-lb. x $10^{6)}$	+7,030	-5,000
		Σ(QD) = 2,030 $\times$ 10^6 in.^{2}-lb	
	Operation	**Stress, ksi**	
8	Gates stationary Δ = 0	9.9	9.4
9	Gates being opened Δ = +4.4	3.4	16.8
10	Gates being closed Δ = +4.6	16.7	1.5

1 kip per in.^{2} Stresses which occur during normal operation of the gate are computed from

$$s = \frac{RE}{L}(D - \Delta) \tag{3-24}$$

and are placed in lines 8, 9, and 10.

From Table 3-6, it is seen that the diagonal sizes chosen are quite satisfactory.

h. Method of prestressing. The turn-of-the-nut method will be used. After the diagonals are made slack, the deflection of the leaf is measured in the field. Since this actual initial deflection is unknown at this time, the theoretical value will be used (with diagonals slack *Q* - zero).

$$\Delta = \frac{\Sigma T_z + \Sigma Q_D}{Q_o + \Sigma Q} = \frac{\Sigma T_z}{Q_o} \tag{3-21}$$

$$= \frac{-2{,}020 \times 10^6}{120 \times 10^6} = -16.8 \text{ in.}$$

(1) Diagonal U_oL_1. The slack is removed from this diagonal only and the diagonal is clamped. The required prestress is then obtained by tightening the sleeve nut the following number of turns:

$$\begin{aligned} N &= \frac{nR_o(D - \Delta)}{2} \\ &= \frac{2.5 \times 0.0822}{2}[+6.7 - (-16.8)] \\ &= 2.41 \text{ turns} \end{aligned} \tag{3-27}$$

The torque required to accomplish this is found from Equation 3-28 after determining the resulting leaf deflection from

$$\Delta = \frac{\Sigma T_z + \Sigma Q_D}{Q_o + \Sigma Q}$$

$$= \frac{(-2{,}020 + 1{,}050 \times 6.7) \times 10^6}{(120 + 1{,}050) \times 10^6} \tag{3-21}$$

$$= 4.4 \text{ in.}$$

$$M = \frac{0.18\ REA_d\ (D - \Delta)}{L}$$

$$= \frac{0.18 \times 0.0393 \times 29 \times 10^6 \times 12 \times 4.75\ (6.7 - 4.4)}{771}$$

$$= 35{,}000 \text{ in.-lb} \tag{3-28}$$

or 490 lb required at the end of a 6-ft wrench. In this option it is assumed that both members of diagonal U_oL are prestressed simultaneously.

(2) Diagonal L_oU_1. The theoretical initial deflection of the leaf for this diagonal is the final leaf deflection of 4.4 in. after prestressing the previous diagonal. To prestress this diagonal the required amount, it is necessary to tighten the nut through the following turns, after first removing the slack.

$$N = \frac{2.75\ (-0.0822)\ (-5.5 - 4.4)}{2} \tag{3-27}$$

$$= 1.12 \text{ turns}$$

This tightening will make the leaf plumb ($\Delta = 0$) and will require a maximum torque of:

$$M = \frac{0.18\ (-0.0452) \times 29 \times 10^6 \times 9 \times 4.25\ (-5.5 - 0)}{771}$$

$$= 64{,}000 \text{ in.-lb} \tag{3-28}$$

or 900 lb required at the end of a 6-ft wrench.

(3) Plumb/out of plumb. With the completion of this operation, the leaf will nearly always hang plumb. If it does not, the corrected prestress deflection for this diagonal can be found from Equation 3-21 with Δ equal and opposite to the out-of-plumb deflection. This prestress deflection can then be substituted in Equation 3-27 to obtain the corrected number of turns required to make the leaf hang plumb. For instance, for a final out-of-plumb deflection of +1/2 in., the corrected prestress deflections would be found from $\sum QD = (\Delta Q_o + \sum Q) - (T_z)D.L.$ to be +980 in.^{2}lb $\times$ 10^6. With D for diagonal L_oU_1 maintained at -5.5 in., the D then required for diagonal U_oL_1 would be +5.7 in. and N for this diagonal would become 2.30 turns. The remainder of the computations would be repeated.

3-6. Example 2, Vertically Framed Gate

See Figures 3-9 and 3-10.

a. Evaluation of A′. The cross-sectional area of the bottom girder (see Figure 3-10) is 36.7 in^2, the cross-sectional area of any vertical girder is 37.0 in.^{2}, (see Figure 3-9), and the cross-sectional area of the top girder is 112.5 in.^{2}. Therefore, the value of A' (see definition) for all diagonals is

$$A' = (1/20)\ (36.7 + 74.0 + 112.5) = 11.0 \text{ in.}^2$$

b. Evaluation of R_o, R, and Q. Since this is an existing lock, the diagonal sizes are fixed.

$$R_o = \pm \frac{2wt}{v(w^2 + h^2)^{½}}$$

$$= \pm \frac{2 \times 232t}{723\ (232^2 + 535^2)^{½}} \tag{3-11}$$

$$= \pm\ 0.00110\ t$$

$$R = \frac{A'}{A + A'}\ R_o$$

$$= \pm\ 0.0121 \frac{t}{(A + 11)} \tag{3-13}$$

$$= \frac{11}{(A + 11)}\ R_o$$

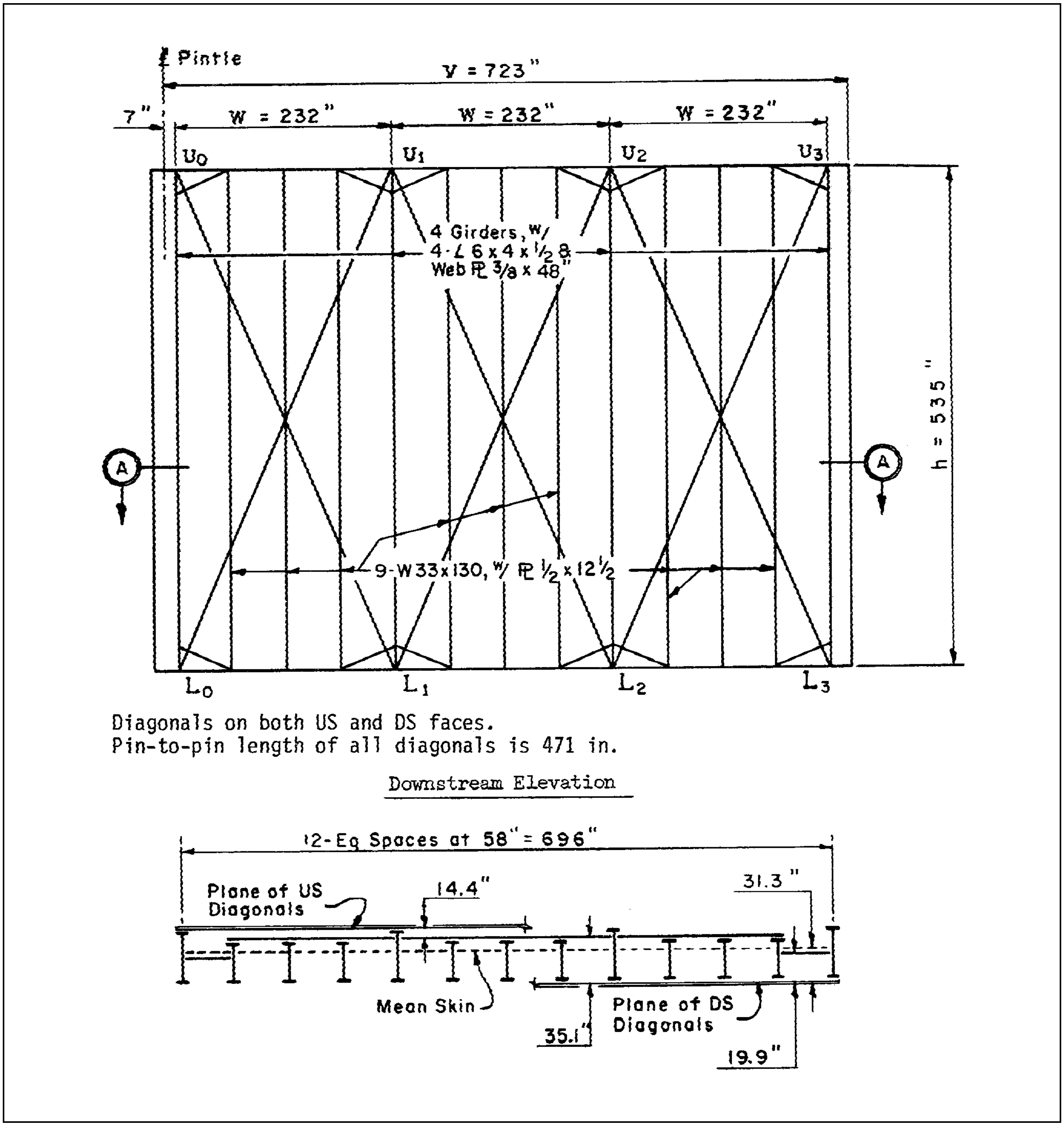


Figure 3-9. Schematic drawing of a vertically framed leaf

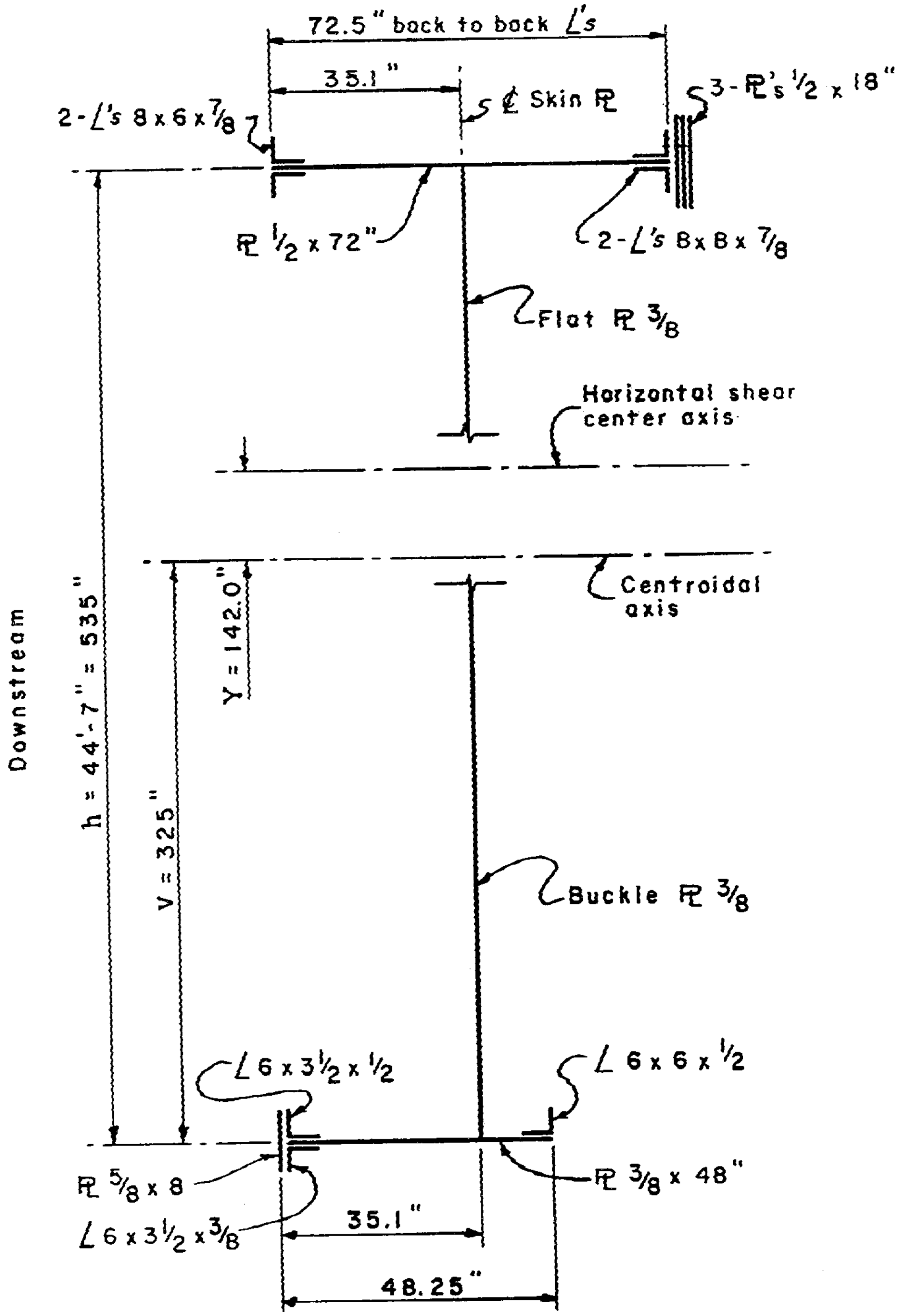


Figure 3-10. Average vertical section through leaf

$$Q = \frac{RR_o EAhv}{L}$$

$$= \frac{RR_o \times 29 \times 10^6 \times A \times 535 \times 723}{471} \qquad (3\text{-}18)$$

$$= 238 \times 10^8 \times RR_o A$$

Computation of the elasticity constant Q is shown in Table 3-7.

(1) Because all the skin in the end panels is not in the same plane, t (in the end panels) is measured from the mean skin shown in Figure 3-9. (See paragraph 3-4*h* for the determination of t for skin not in a plane.)

(2) This example provides a good illustration of the inefficiency of past designs. The upstream diagonals are quite ineffective because they are so close to the skin plate. If all the upstream diagonals were omitted (in other words, the number of diagonals cut in half) and the skin plate placed in their location instead, the leaf would be stiffer and the stresses in the remaining diagonals would be lower. Further, with a flat skin plate, all positive diagonals could have been made the same size and all negative diagonals, another size (for simplification of details and reduction in cost).

c. Evaluation of Q_o. (See paragraph 3-4*i*(2) and Table 3-8.)

$$Q_o = K \times E_s \times \Sigma(J/h + J/v)$$

$$= 4 \times 12 \times 10^6 \left(\frac{310}{3 \times 535} + \frac{700}{3 \times 723}\right) \qquad (3\text{-}26)$$

$$= 25 \times 10^6 \text{in.-lb}$$

d. Location of shear center. (See paragraph 3-5*c*.) Computations for the centroidal axis and the moment of inertia of the vertical section through the leaf (see Figure 3-9) are not shown.

Table 3-7
Computation of Elasticity Constant *Q*

Diagonal	A (in.^{2})	t (in.)	R_o	R	Q (in.lb × 10^6)
[a] D'stream U_oL_1	10.00	31.5	+0.0347	+0.0182	150.0
[a] D'stream U_1L_2	8.00	35.2	+0.0388	+0.0224	165.0
[a] D'stream U_2L_3	4.50	31.3	+0.0345	+0.0244	90.0
[a] Upstream L_oU_1	4.50	18.3	+0.0202	+0.0143	31.0
[a] Upstream L_1U_2	4.50	14.4	+0.0159	+0.0112	19.0
[a] Upstream L_2U_3	4.50	17.9	+0.0197	+0.0140	30.0
[b] Upstream U_oL_1	10.00	17.2	-0.0189	- 0.0099	45.0
[b] Upstream U_1L_2	8.00	13.3	-0.0146	- 0.0085	24.0
[b] Upstream U_2L_3	4.50	17.0	-0.0187	- 0.0133	27.0
[b] D'stream L_oU_1	4.50	32.6	-0.0359	- 0.0255	98.0
[b] D'stream L_1U_2	4.50	36.2	-0.0399	- 0.0282	120.0
[b] D'stream L_2U_3	4.50	32.2	-0.0355	- 0.0252	96.0
					ΣQ = 895

[a] Positive diagonals
[b] Negative diagonals

Table 3-8
Computation of Modified Polar Moment of Inertia J

Elements	n No. of Elements	1 (in.)	c (in.)	Horizontal Members	Vertical Members
Horiz. Girders					
U/S flange,	1	18.0	2.38	240	
Web, (Top)	1	72.0	0.50	10	
D/S Flange,	2	14.0	0.88	20	
U/S flange,	1	12.0	0.50	0	
Web, (Bottom)	1	48.0	0.38	0	
D/S flange	1	8.0	1.13	10	
Skin plate	1	535.0	0.38	30	
Vertical Girders					
U/S flange	8	10.0	0.50		10
Intermed. flange	6	7.0	0.38		0
Web	4	48.0	0.38		10
U/S flange	8	10.0	0.50		10
Vertical Beams	9	11.5	1.73		540
US flange	9	31.4	0.58		60
Web	9	11.5	0.86		70
D/S flange					
				Total = 310	700

y = 325 in.
$I = 14.3 \times 10^6 \text{in.}^4$

Horizontal shear center axis:

Moment of inertia of:
Top girder = 84,100 in.^{4}

$$Y = \frac{\Sigma(I_n \cdot y)}{\Sigma I_n} = \frac{84{,}100 \times 210 - 12{,}100 \times 325}{96{,}200} = +142 \tag{3-29}$$

Vertical shear center axis:

Computation of the distance X is shown in Table 3-9.

$$X = -\left[\frac{\Sigma(ayby_n)}{I}\right] = -\left(\frac{-69.9 \times 10^6}{14.3 \times 10^6}\right) = +4.9 \text{ in.} \tag{3-30}$$

e. Load torque areas. (See discussion in paragraph 3-4*i*(3).) The forces which produce twisting of the leaf are shown in Figure 3-11. Again, computations for locating the center of gravity and deadweight of the leaf are not shown. Since this is a 9-ft channel handling only shallow-draft vessels, a water resistance of 30 psf is used.

For dead load: T_z = -235,000 (10.7 + 4.9) × 355
= -1,300 × 10^6in.^2-lb

Table 3-9
Computation of Distance *X* for Vertically Framed Gate

Girder	*a* (in.^{2})	*b* (in.)	*y* (in.)	y_n (in.)	$ayby_n$ (in.$^5 \times 10^6$)
Top girder - U/S	62.8	+37.4	+210	+ 68	+ 33.5
Top girder - D/S	31.8	- 35.1	+210	+ 68	- 15.9
Bottom girder - U/S	8.2	+13.1	-325	-467	+ 16.3
Bottom girder - D/S	19.5	- 35.1	-325	-467	-103.8
					Σ = - 69.9

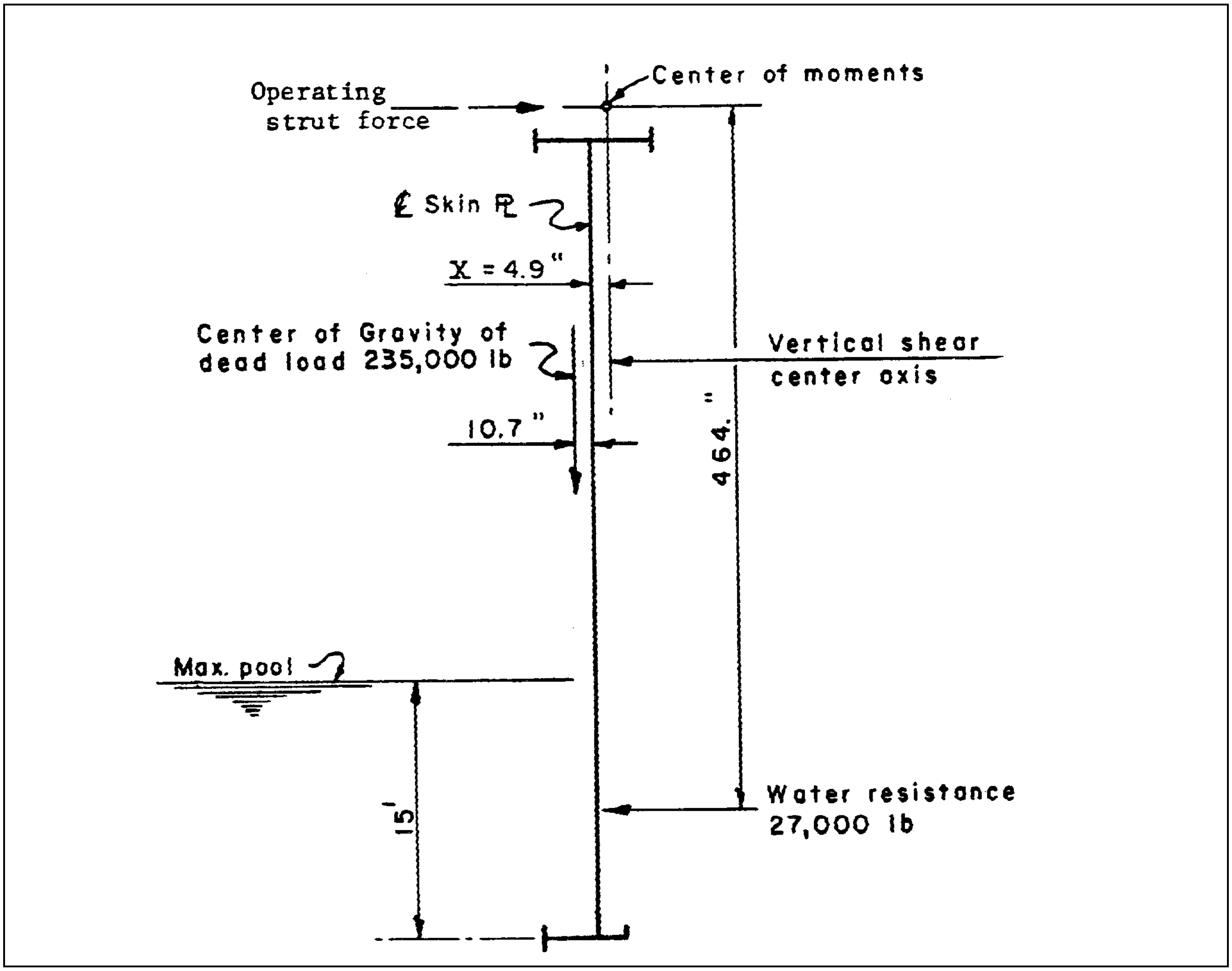


Figure 3-11. Torsional forces on leaf

For live load: $T_z = \pm 27{,}000 \times 464 \times 362$
$= \pm 4{,}350 \times 10^6$ in.^{2}-lb
(positive value for gate opening)

f. Deflection of leaf.

$$\Delta = \frac{\Sigma T_z}{Q_o + \Sigma Q} \qquad (3\text{-}23)$$

$$= \frac{\pm\ 4{,}530 \times 10^6}{(25 + 895) \times 10^6} = \pm 4.9 \text{ in.}$$

Where positive value is for gate opening.

g. Prestress deflections and stresses in diagonals. The prestress deflections are determined in Table 3-10. The minimum numerical values of D (column 4) are the maximum deflections of the leaf. Maximum numerical values of (D - Δ) are found by solving Equation 3-24

$$(D - \Delta)\ \max = \frac{sL}{RE}$$

$$= \frac{18{,}000 \times 471}{R \times 29 \times 10^6} = \frac{0.292}{R}$$

Having the maximum numerical values of (D - Δ), the maximum numerical values of D are determined and placed in column 6. Values of D (column 7) are then selected such that Equation 3-22 is satisfied; that is, ΣQD must equal +1,300 × 10^6 in.^{2}-lb. Because all but the top 10 ft of the skin consists of buckle plates (see paragraph 3-4*i*(4)), an attempt is made to have the diagonals carry as much of the vertical dead load shear as possible. Therefore, values of D are made as large as possible for the diagonals extending downward toward the miter end, and as small as possible for the other diagonals. Further, to ensure that the diagonals are always in tension, D should also be such that the minimum stress is more than 1,000 psi. The unit stresses in the diagonals are found from

$$s = \frac{RE}{L}(D - \Delta) \qquad (3\text{-}24)$$

Before computing normal stresses (columns 10, 11, and 12), the stresses which occur during the prestressing operation are computed (column 9) as a check on the value of D. The twist-of-the-leaf method for prestressing is used. Because of the large value of D for some of the negative diagonals, it is best to prestress all negative diagonals first.

h. Dead load shear in skin: (buckle plates). Prestressing of many gates in the Rock Island District has proved that buckle plates can support the shear imposed on them during and after the prestressing operation without any apparent distress. However, it is still considered desirable to have the diagonals carry as much of the vertical dead load shear as possible. If the skin had been flat plate, this consideration would have been omitted. In Table 3-11 the dead load shear remaining in the skin (buckle plates) is determined.

i. Method of prestressing. The twist-of-the-leaf method will be used as outlined in paragraph 3-4*j*(1). The maximum force will be required when the leaf is deflected +10.0 in. against the action of the negative diagonals (which are prestressed, in this case, first).

$$P = \frac{\Delta\ (Q_o + \Sigma Q) - \Sigma QD - (\Sigma\ T_z)DL}{hv}$$

$$= \frac{[+10.0\ (25 + 410) - (2{,}620) - (-1{,}300)] \times 10^6}{535 \times 723}$$

$$= 21{,}000 \text{ lb}$$

Upon completion of this prestressing operation, the leaf is very rarely out of plumb. Should it be, however, the corrected prestress deflections can be found from Equation 3-21 with Δ equal and opposite to the out-of-plumb deflection, as follows.

$$\Sigma QD = \Delta\ (Q_o + \Sigma Q) - (\Sigma T_z)_{DL}$$

In this example, for a final out-of-plumb deflection of +½ in., revised values of D would be selected to make ΣQD equal to +840. × 10^6 in.^{2}-lb. The leaf would then hang plumb. Repeat computations, if necessary.

3-7. Vertical Paneling of Leaf

The previous design applies to miter gate leaves that are divided into panels (not necessarily equal) longitudinally. With a slight modification of the term R_o the design is extended to apply to leaves that are divided into panels vertically as well as longitudinally. Figure 3-12 shows the most general arrangement of paneling. In practice, an effort would be made to make the panel heights and widths the same. To design the diagonals use

Table 3-10
Computation of Diagonal Stresses

TABLE 3 - 10 COMPUTATION OF DIAGONAL STRESSES

			POS. DIAGONALS						NEG. DIAGONALS					
1	DIAGONAL		D. S. U_0L_1	D. S. U_1L_2	D. S. U_2L_3	U. S. L_0U_1	U. S. L_1U_2	U. S. L_2U_3	U. S. U_0L_1	U. S. U_1L_2	U. S. U_2L_3	D. S. L_0U_1	D. S. L_1U_2	D. S. L_2U_3
2	R		+0.0182	+0.0224	+0.0244	+0.0143	+0.0112	+0.0140	-0.0099	-0.0085	-0.0133	-0.0255	-0.0282	-0.0252
3	Q IN. - LB X 10^6		150	165	90	31	19	30	45	24	27	98	120	96
4	MINIMUM NUMERICAL VALUE OF D		+4.9	+4.9	+4.9	+4.9	+4.9	+4.9	-4.9	-4.9	-4.9	-4.9	-4.9	-4.9
5	MAXIMUM NUMERICAL VALUE OF (D - Δ)		+16.1	+13.0	+12.0	+20.4	+26.1	+20.8	-29.5	-34.3	-22.0	-11.4	-10.3	-11.6
6	MAXIMUM NUMERICAL VALUE OF D		+11.2	+8.1	+7.1	+15.5	+21.2	+15.9	-24.6	-29.4	-17.1	-6.5	-5.4	-6.7
7	D		+10.0	+7.5	+6.5	+7.5	+7.5	+7.5	-12.0	-12.0	-5.25	-6.25	-5.25	-5.25
8	QD IN^2 - LB. X 10^6		+1500	+1240	+590		+600		-830		-140		-1,650	
9	STRESS, LB / SQ. IN.	DURING PRESTRESSING Δ = + 10.0 IN.	PRESTRESSED LAST						13,400	11,500	12,500	23,900	26,400 a	23,600
10	STRESS, LB / SQ. IN.	GATE STATIONARY Δ = 0	11,200	10,300	9,800	6,600	5,200	6,500	7,300	6,300	4,300	8,300	9,100	3,100
11	STRESS, LB / SQ. IN.	GATE BEING OPENED Δ = + 4.9 IN.	5,700	3,600	2,400	2,300	1,800	2,200	10,300	8,800	8,300	15,900	17,600	15,700
12	STRESS, LB / SQ. IN.	GATE BEING CLOSED Δ = -4.9 IN.	16,700	17,100	17,100	10,900	8,500	10,700	4,300	3,700	300	600	600	600

$\sum QD = +1,310$

a TOO HIGH, BUT INHERENT IN THIS EXISTING GATE.

Table 3-11
Computation of Dead Load Shear in Buckle Plates

Panel	Diagonal	A (in.^{2})	s (lb/in.^{2})	As (lb)	$\Sigma(As \frac{h}{L})$ (lb)	Panel	Skin
	DSU_oL_1	10.0	11,200	+112,000			
0-1	USU_oL_1	10.0	7,300	+ 73,000			
	USL_oU_1	4.5	6,600	- 29,000	+119,000 lb	- 196,000 lb	+77,000 lb
	DSL_oU_1	4.5	8,300	- 37,000			
	DSU_1L_2	8.0	10,300	+ 82,000			
1-2	USU_1L_2	8.0	6,300	+ 50,000			
	USL_1U_2	4.5	5,200	- 23,000	+ 68,000	+117,000 lb	+49,000 lb
	DSL_1U_2	4.5	9,100	- 41,000			
	DSU_2L_3	4.5	9,800	+ 44,000			
2-3	USU_2L_3	4.5	4,300	+ 19,000			+41,000 lb
	USL_2U_3	4.5	6,500	- 29,000	- 2,000	- 39,000 lb	
	DSL_2U_3	4.5	8,100	- 36,000			

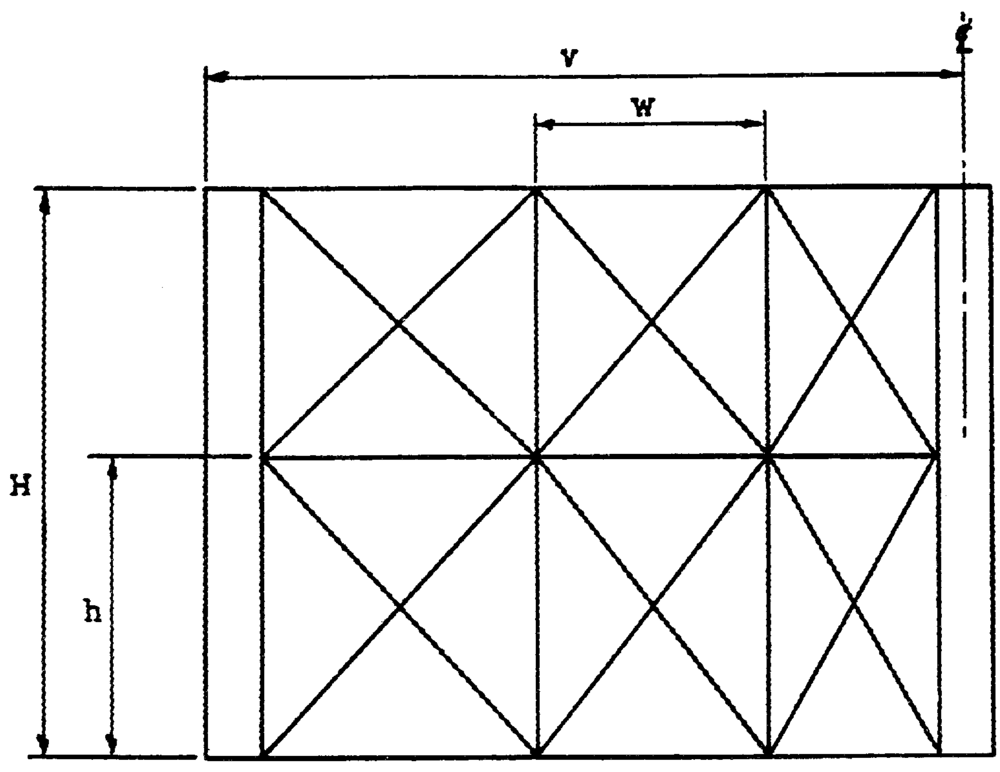


Figure 3-12. Vertical and longitudinal arrangement of leaf panels

$$R_o = \pm \left(\frac{2w \cdot h \cdot t}{H \cdot v \cdot (w^2 + h^2)^{1/2}} \right) \tag{3-11$'$}$$

This value of R_o replaces that given in Equation 3-11, being a more general expression. It is seen that for a value of $h = H$ (no vertical paneling) Equation 3-11′ reverts to Equation 3-11. With the above value of R_o, all the other expressions and the method of analysis remain identical to that previously outlined.

3-8. Derivation of Equation 3-11′

The general value of R_o can be found as follows. (Refer to paragraph 3-4*d*). Let d = deflection of panel; other symbols are as defined previously. Figure 3-13 illustrates the displacements of points of a vertical divided panel.

Let δ_o = change in length of any diagonal

$$\delta_o = \left(\frac{d}{w}\ t \cos \alpha \right) + \left(\frac{d}{h}\ t \sin \alpha \right)$$

$$= \frac{d\ t}{w} \left[\frac{w}{(w^2 + h^2)^{1/2}} \right]$$

(See Figure 3-13)

$$+ \frac{d\ t}{w} \left[\frac{h}{(w^2 + h^2)^{1/2}} \right]$$

$$\delta_o = \left[\frac{2dt}{(w^2 + h^2)^{1/2}} \right]$$

Where h and d are the height and deflection of *one* panel

then

$$r_o = \frac{\delta_o}{d} = \pm \left[\frac{2t}{(w^2 + h^2)^{1/2}} \right]$$

The relation between the deflection of the panel and the leaf becomes

$$d = \left(\frac{w}{v} \right) \left(\frac{h}{H} \right) \Delta \quad \text{or} \quad \Delta = \left(\frac{v}{w} \right) \left(\frac{H}{h} \right) d$$

$$R_o = \frac{\delta_o}{\Delta} = \left[\frac{2dt}{(w^2 + h^2)^{1/2}} \right] \left[\frac{1}{\left(\frac{v}{w} \right) \left(\frac{H}{h} \right) d} \right] \tag{3-11$'$}$$

$$R_o = \pm \left[\frac{2w\ h\ t}{H\ v\ (w^2 + h^2)^{1/2}} \right]$$

The remainder of the expressions are the same as before, for distance

$$R_o = \frac{\delta}{\Delta} = \frac{r\ d}{\left(\frac{v}{w} \right) \left(\frac{H}{h} \right) d} = \left(\frac{w}{v} \right) \left(\frac{h}{H} \right) r$$

$$= \left(\frac{w}{v} \right) \left(\frac{h}{H} \right) \left(\frac{A'}{A + A'} \right)$$

$$R_o = \left(\frac{w}{v} \right) \left(\frac{h}{H} \right) \left(\frac{A'}{A + A'} \right) \pm \left(\frac{2t}{(w^2 + h^2)^{1/2}} \right)$$

Therefore

$$R_o = \pm \left[\frac{2w\ h\ t}{H\ v\ (w^2 + h^2)^{1/2}} \right] \left(\frac{A'}{A + A'} \right)$$

$$= R_o \left(\frac{A'}{A + A'} \right)$$

In similar manner it can be shown that the expressions for Q and Q_0 (Equations 3-18 and 3-26, respectively) still apply with H substituted for h.

3-9. Temporal Hydraulic Loads

The effect of temporal hydraulic loads on the miter gate diagonal design will be evaluated at each lock with appropriate conditions selected for the design. A minimum temporal hydraulic load of 1.25 ft (with a period exceeding 30 sec) will be used for gate diagonal design if it governs, with a leaf submergence corresponding to

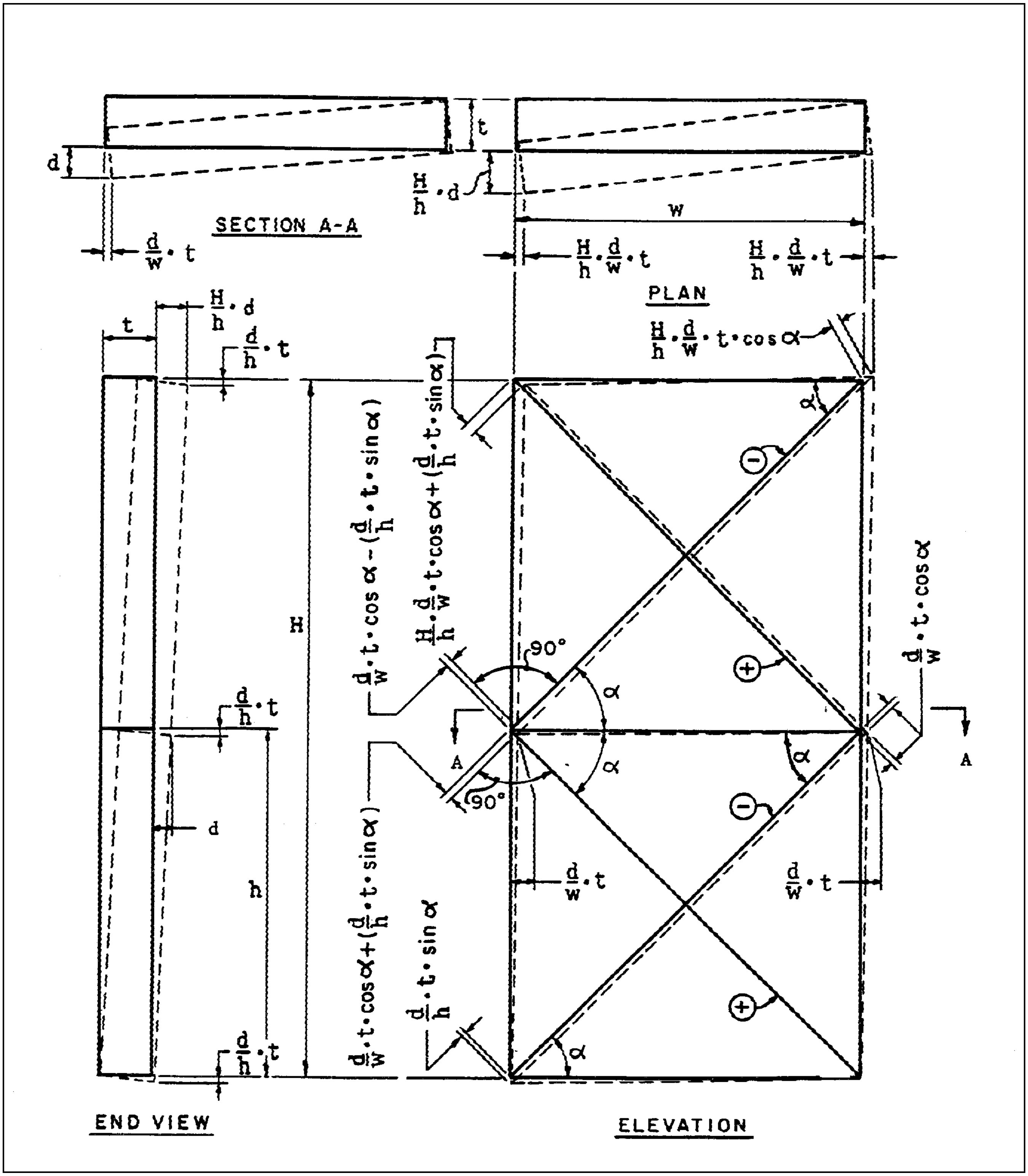


Figure 3-13. Displacement of points of a vertical divided panel

normal navigation pool conditions. For this load condition, a 33-1/3 percent overstress is allowed for diagonal design. Temporal hydraulic loads in the lock chamber and/or lock approaches may be caused singly or in combination by the following:

a. Wind waves and setup.

b. Ship waves.

c. Propeller wash.

d. Lock overfill and/or overempty.

e. Lock upstream intake and downstream exit discharges.

f. Landslide waves.

g. Tributary and/or distributary flow near lock.

h. Surges and reflected waves in canals.

i. Seiches.

j. Changes in spillway or powerhouse discharges.

k. Tides.

3-10. Procedure for Prestressing Diagonals

a. The following steps establish a procedure for prestressing diagonals. There are different procedures for stressing diagonals, this being just one. Use Figure 3-14 with this procedure.

(1) With all diagonals slack, adjust anchorage bars so quoin end is plumb and bottom girder is horizontal. Pintle shoe shall be fully seated against the back of the pintle base.

(2) Lubricate the nuts on the diagonals so they can turn easily.

(3) Place rosettes for strain gages on all diagonals a minimum of 20 hours before prestressing unless an approved quick-setting cement is used.

(4) Without the restraint of any guys or jacks, the leaf will deflect in a negative direction under its own dead load weight. Measure this deflection.

(5) Guy the leaf at its miter end to the tieback anchor and place jacks at the miter end.

(6) Jack the miter end away from the wall until the leaf has a deflection equal to D_1.

(7) Hold the deflection and tighten diagonals 1 and 3. Tighten these diagonals so that there is no horizontal bow. Do not attempt to remove all vertical sag.

(8) Tighten diagonals 2 and 4.

(9) Proceed with the jacking until a deflection D_2 is obtained. During this operation do not change the adjustment of diagonals 1 and 3. However, continue tightening diagonals 2 and 4 until there is a slight tension in the members when the leaf is in its final deflection position.

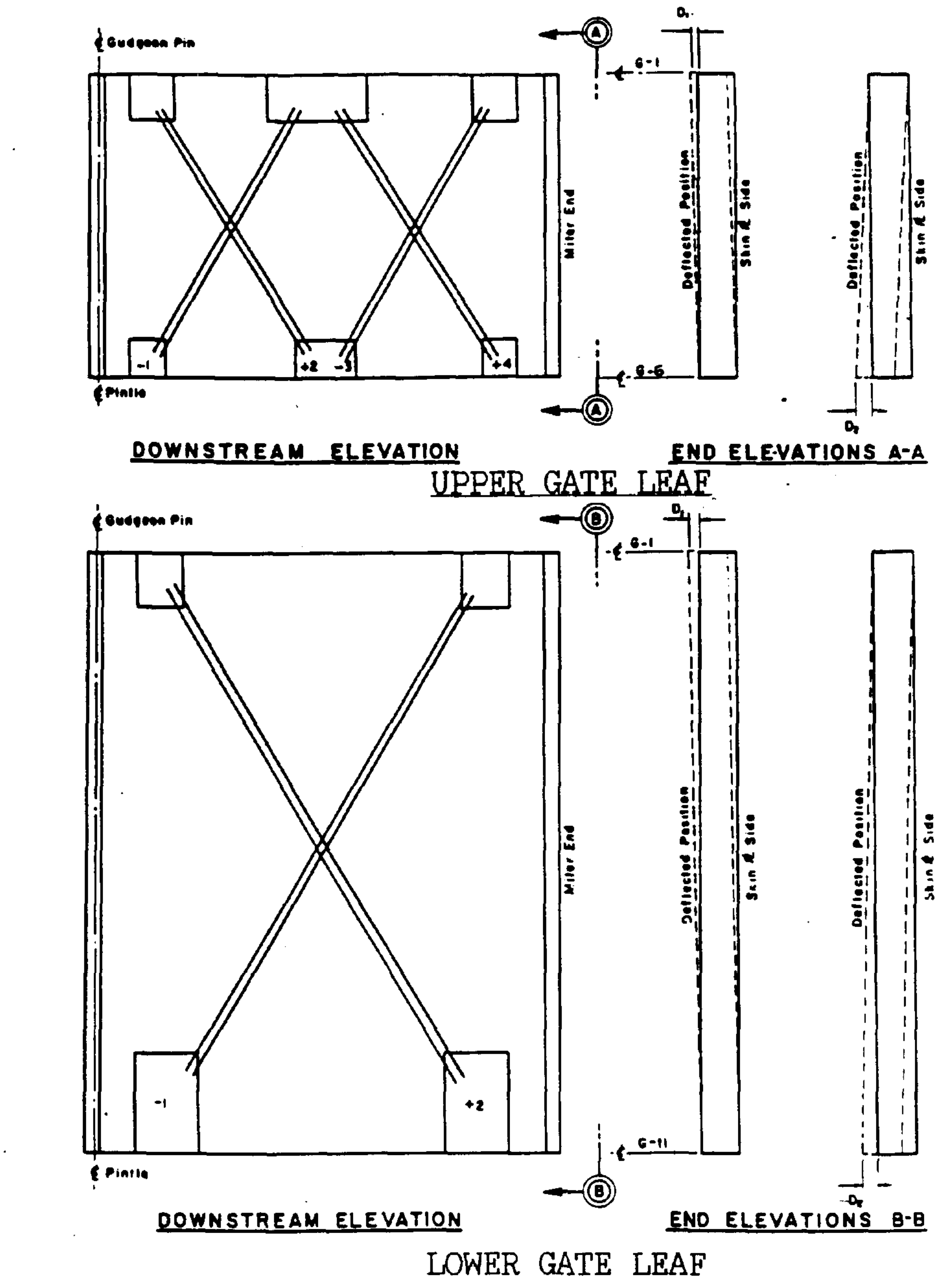
(10) During the prestressing operation use a strain gage to determine the stress in the diagonals. The maximum allowable stress shall be $0.75F_y$.

(11) After the final adjustments of the diagonals remove the guys and jacks. The leaf should return to the plumb position. A deflection $\pm$1/4 in. will be permitted in the lower leaf and $\pm$1/8 in. on the upper leaf. A larger tolerance is allowed for the lower leaf because it is much taller than the upper leaf.

(12) Final minimum and maximum stresses, unless otherwise approved by the Contracting Officer, shall be $0.45F_y$ minimum and $0.55F_y$ maximum for all diagonals.

3-11. New Information on Diagonal Design

a. New preliminary information has been gained through the finite element study made by Drs. L. Z. Emkin, K. M. Will, and B. J. Goodno of the Georgia Institute of Technology regarding torque tubes and leaf stiffness (USAEWES 1987). For all current gates designed with the 2.5-ft differential head, it appears that the values arrived at through the finite element analysis of Bankhead Lock lower gate in Tuscaloosa, AL, are realistic. This includes the values of leaf stiffness without diagonals, with diagonals, and with horizontal top and bottom torque tubes. These values are only a recommendation and consideration should be given to any variation in leaf configuration and modifications made to adjust the design factors accordingly.



NOTE:

A deflection of the leaf is defined as a twisting of the leaf such that the miter end is out of plumb. A positive deflection of the leaf is one in which the top of the miter end is moved upstream relative to the bottom. The magnitude of the deflection is the amount by which the top of the miter end is out of plumb, as shown in the figure.

When any diagonals are tightened, they shall be taken up just to the point where all of the slack is removed and a very slight tension exists. Care shall be exercised that the amount of this initial tension is as small as possible. The slack shall be considered to be removed when the diagonal does not bow in or out from the leaf. No attempt shall be made to remove the slight vertical sag which will always exist in the diagonal because of its dead weight.

Figure 3-14. Methods for prestressing diagonal

b. The use of top and bottom torque tubes is suggested as a suitable means of increasing leaf stiffness, although it appears that the conventional method of prestressing by twisting the leaves with a jack may need to be altered. On the Oliver Lock in Tuscaloosa, AL, where the torque tubes were used and diagonals sized for surge loading, it appeared that the twist-of-the-leaf method of prestressing the diagonals had about reached its maximum. Due to the increased leaf stiffness and corresponding jack capacity ($\pm$ 150 tons), it appeared that damage to the leaf, such as localized buckling of plates, excessive deflection of the quoin post, damage to the grease seals, pintle, pintle socket, etc., could be imminent.

c. The values representing leaf stiffness for this particular study were determined to be:

Q_o = stiffness factor of leaves without diagonals

Q_d = stiffness factor of diagonals

Q_t = stiffness factor of top and bottom torque tubes (One 6-ft girder space at top and one 4-ft girder space at bottom)

$Q_d = 2.4Q_o$

$Q_t = Q_o$

d. It is recommended that consideration be given to prestressing new gate leaves with torque tubes by turning the nuts on the ends of the diagonals and using suitable means to prevent twisting of the diagonals. This would simplify the prestressing and reduce the risk of damage to the gate leaves as well as reduce the risk to personnel. There may be commercial sources that have equipment available that could be readily adapted to this means of prestressing, as has been the case in prestressing the anchor bolts of the embedded anchorage.

e. Additional studies are needed to advance the understanding of miter gate leaf stiffness. Significant factors are dead load deflection, jack loads, if used, strain gage readings, problems encountered, alignment of gudgeon pin over pintle, and any other information thought to possibly be pertinent. For additional information see USAEWES (1987).